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STUDIES OF POWER-SHOVEL OPERATION SHOW POSSIBILITIES OF INCREASED EFFICIENCY

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TABLE OF CONTENTS

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POWER-SHOVEL OPERATION IN HIGHWAY GRADING

A REPORT OF OBSERVATIONS MADE ON GOING PROJECTS BY THE DIVISION OF MANAGEMENT, BUREAU OF PUBLIC ROADS

Reported by T. WARREN ALLEN, Chief, Division of Management, and ANDREW P. ANDERSON, Associate Highway Engineer

PART 1.—AN OUTLINE OF MORE IMPORTANT FACTS DEVELOPED IN STUDIES AND DISCUSSION OF FACTORS AFFECTING THE OPERATING CYCLE OF THE SHOVEL

THE DAILY cost of operating a power-shovel grading outfit is very nearly fixed for any given set of conditions, regardless of whether the output is high or low. The only effective means available to the contractor for reducing his unit cost is therefore to increase the rate of production. Some of the more general requirements necessary for efficient, economical production as developed will be briefly summarized in the first portion of this article and treated in greater detail in subsequent portions of this series of articles.

Efficient use of the power shovel in highway grading generally involves the proper coordination of at least three distinct operations: (1) Except where the material can be cast, it must be dug and loaded into the hauling units at or near the maximum rate of production for the material handled; (2) the hauling units must be just sufficient to carry the output of the shovel and must be operated with almost clocklike precision, so that the load may be received, transported to the place of disposal, dumped, and the hauling units returned to the shovel without interrupting the steady operation of the shovel; (3) at the fill or dump the material brought by the hauling units must be spread and compacted or otherwise cared for as may be required by the specifications without interfering with the steady operation of the hauling units. If the material is too hard to be dug effectively with the shovel, another operation, that of drilling and blasting, is necessary, and this operation must also be carried on without interfering with the others.

Efficient operation requires not only that a high rate of production be secured with the shovel, but that this production be secured with the use of a minimum of labor and auxiliary equipment. This can only be accomplished when each operation is so synchronized and coordinated that the entire organization functions as a unit without either interference or waste in any of its parts. Absolute perfection in all details is probably impossible. Nevertheless, recent extensivestudies by the Division of Management of the Bureau of Public Roads, of power-shovel operation on a large number of projects operated under a great variety of conditions show rather conclusively, (1) that a high degree of efficiency is possible of attainment, and (2) that, in general, the cause of the low production encountered on many projects is due to conditions over which the management has more or less definite control and which are therefore to some extent remediable.

On this work the shovel is the primary producer. All production is dependent on it. An inferior shovel or operator is a certain guarantee that production costs will be high. The shovel should be sturdy, powerful, dependable, fast, and easily operated. But no matter how good the shovel, a high grade of skill, intelligence, and endurance is required on the part of the operator in order to secure consistently a high rate of production.

In ordinary common excavation 4 or more feet in depth and which is dug easily and dumped freely, a good power shovel in good condition can load vehicles at the rate of four dipper loads per minute, providing the vehicles are so placed that the average swing does not exceed 90°. A good operator can continue this rate for intermittent periods throughout the day. To attain this rate it is necessary to load the dipper in about $4\frac{1}{2}$ seconds, to swing and spot the dipper in about 4 seconds, to dump it in $1\frac{1}{2}$ seconds, and then return the dipper to the loading point in about 5 seconds. Many jobs have been found where this rate has been maintained during intermittent periods of varying length under the conditions given above, and it may therefore be taken as the maximum attainable with present-day power shovels worked under favorable field conditions. However, numerous jobs have

DATA COLLECTED in studies of power-shovel operation, which are reported in this series of articles, indicate that there are few jobs on which a material increase in output can not be obtained without a corresponding increase in cost. In some cases it has been found possible to increase output as much as 100 per cent by a change in management methods.

Under favorable conditions a good operator can attain a rate of loading of four dipper loads per minute for intermittent periods and three dipper loads or more per minute as a continuous rate. By whatever amount the contractor fails to attain this rate under favorable conditions, he is failing to attain the maximum possible efficiency.

Efficiency of production can not exceed the efficiency of the shovel operator. To change an operator making a load every 18 seconds for one who takes 20 seconds reduces the output 10 per cent. This can easily amount to \$20 to \$25 a day in lost profits.

The difference in time required to make a 90° swing in loading and to make a 180° swing may reduce the output by as much as 25 per cent.

A mass diagram is essential in planning hauling equipment and estimating on a job. With such a diagram, and knowing the time constants of operation, it is possible to determine the most efficient outfit and how long it should take to do the work.

Determination of proper team supply greatly affects profits. One job is estimated to cost \$15,440 with an 8-team outfit which can be done for \$14,555 with an 11-team outfit.

It is often advantageous to sublet short-haul work or to do it with wheelers or fresnoes when conditions result in a surplus of teams at the shovel.

Work should be continued under adverse conditions when it is possible to earn more than the difference between the costs which accrue while working and those which accrue while idling.

It has been found that the diversity of kinds and sizes of trucks has produced varied results in meeting the specialized requirements of use with a power shovel.

Using trucks on a short haul, it has sometimes been found possible to double the output by backing them to the dump rather than making a turn at the dump and another at the shovel.

Roadway conditions play an important part in truck operation. Pneumatic tires, particularly those of the dual type, are preferable.

Crawler-type tractors drawing large dump wagons have been found adapted to conditions commonly found on power-shovel jobs. The number of trains used must agree closely with economical requirements. As an example, the use of one 2-wagon train on a particular job requiring two such trains would have increased the cost of the job nearly \$7,200, while the use of three trains would have increased it \$1,250.

85094—28——1

been found where the average rate of all-day shovel operation, in good common, was at the rate of three or more dipper loads per minute, and this may therefore be accepted as a criterion of good operation under normally favorable field conditions. If the operator is forced to swing his shovel 180° instead of 90°, his best possible short time output will be only about 3⅙ dipper loads per minute even with a very fast swinging shovel, while his all-day average rate may readily be much less than 2½ dipper loads per minute.

Output, however, is the product of the number of dipper loads multiplied by the average yardage per

A FULL DIPPER LOAD OF EASILY WORKED MATERIAL AND A SHORT SWING. SUCH CONDITION SHOULD PRODUCE A LARGE OUTPUT

dipper load. A good operator can combine both speed and high average quantity of material. In ordinary common excavation 3 or more feet in depth the average dipper load for a ¾-yard shovel should be about one-half cubic yard of material as measured in place. A 1-yard dipper should average about 0.7 cubic yard. In some materials which heap up on the dipper and do not spill on the swing the average load will sometimes equal the rated capacity. In poorly blasted rock or shale, or in material full of roots and stumps, the average dipper load may be 40 per cent less than the general average for ordinary common excavation or about 0.3 cubic yard for a ¾-yard dipper. Figure 1 is illustrative of the studies made and shows the rate at which dipper loads can be deposited in the hauling units under fast operation, and how a few slow operations increase the average time per cycle for the entire period. As the material passes from good common to one more difficult the digging and loading operations become slower and there is greater difficulty in securing a full dipper.

MISTAKES IN MANAGEMENT FOUND WHICH GREATLY REDUCE PROFITS

The custom of loading the hauling units at the rear of the shovel (180° swing) is a very expensive practice. Even with a fast-swinging shovel, loading at the rear of the shovel instead of at the side will increase the time required for each dipper load about four seconds, and if the shovel is of slow-swing speed it may be twice this amount. If the average time per dipper load is 20 seconds when loading at the side of the shovel, it will be somewhere between 24 and 28 seconds if the loading is at the rear. In other words, production will be cut from 180 dipper loads per hour to 150 or possibly as low as 128 per hour. Consequently, one of the essential requirements for high-shovel production is to so place the wagons or trucks that the swing of the shovel will be as short as possible.

For materials which clear the dipper freely the dumping time should not, in general, exceed an average of about one second, but sticky, adhesive materials require much skill on the part of the operator, if the average dumping time is to be held down to two or three seconds. A slow or inexperienced operator may readily consume two or three times as much time per dipper load. Daily production in very sticky or adhesive materials may therefore be as low as for poorly blasted rock.

The general tendency among highway grading contractors seems to be to do too little blasting as well as too little clearing and grubbing. It is not uncommon to find power shovels producing only about one-half the output which would have been possible had the blasting been well done. In materials which are too hard to dig readily without blasting, a good powder man is indispensable for satisfactory production.

In shallow cuts attention should be given to the time required to move the shovel forward. A modern crawler-type shovel in good condition can be moved forward in 15 seconds. If an average of 30 seconds is required, either the operator is slow or else the mechanism needs attention. The old-style wheel-traction type operating on mats will ordinarily require from five to seven times as long to move. This is a severe handicap where much shallow cutting is involved. In shallow cuts keeping the boom lower than normal and the shovel well forward will facilitate filling the dipper, while in deep cuts the boom should be kept high and the shovel well back from the face.

On the jobs studied an inadequate supply or poor operation of hauling equipment, or both, were the most frequent causes of slow-shovel operation in good common excavation. Trimming to grade and dressing slopes was the second most prolific cause for extending the time required per dipper load.

If the highest possible shovel production is to be secured, vehicles must be exchanged within the time required to handle one dipper load, or in good common from about 12 to 18 seconds. To operate the hauling equipment so as to meet this requirement is practical under ordinary field conditions, providing each vehicle can carry two or more dipper loads per load. It is not possible to so synchronize the operation of the hauling equipment that high production can be maintained consistently if only one dipperful is carried per load.

NUMBER OF HAULING UNITS NEEDED REQUIRES CAREFUL CONSIDERATION

Since the shovel can, in general, only dig material when vehicles are in position to receive it, the adequacy of the hauling equipment has a very decided effect on production. The number of hauling units of any given kind which are required varies almost directly as the length of haul which generally varies between rather wide limits and often at rapid, irregular rates. The characteristics which affect the rate at which the material can be dug by the shovel sometimes also change with unexpected frequency. In practice, therefore, it is found inadvisable to attempt to maintain an exact balance between the hauling equipment supplied and that just needed to maintain the highest rate of production at the shovel. Consequently, ii. many instances a definite number of hauling units d sent out and maintained on the job until it is completeh The result is that on very short hauls some of the equipment is idle or working at slow rate, while on the longer hauls not enough equipment is available to keek

the shovel at a high rate of production. The question thus becomes one of determining what hauling equipment should be sent out in order to complete the job at the lowest possible cost.

Since it is general practice to maintain a fairly definite number of hauling units on the job, the utilization of the otherwise idle time on the short hauls therefore becomes a matter of considerable importance. At present, the general practice is to begin the fill at the nearest point of the cut, so that as the work proceeds the distance between the shovel and the dump continually increases. The result is that a large portion of the hauling equipment is idling when the cut is begun, but before the end is reached the shovel is waiting a considerable portion of the time. A better method which can frequently be employed is to begin the fill at the balance point or a sufficient distance away from the beginning of the cut, so that as the work proceeds the dump and the shovel will both progress in the same direction and with a haul sufficient to utilize the full equipment to the best advantage. Whenever possible the placing of fills should be so planned that the idle-time loss for the hauling equipment will be reduced to a minimum. Surplus teams may often be used with fresnoes to do cleaning-up work usually done with the shovel.

Various types of hauling equipment are used with the power shovel, the most common of which are teams and bottom-dump wagons, motor trucks, and large tractor-drawn bottom-dump wagons. Teams are used more frequently than any other type, and in general, are very satisfactory for short to moderate hauls. The time required for turning, dumping, and maneuvering is relatively short and their average round-trip speed fairly constant at from about 220 to 240 feet per minute over a wide range of road conditions. On jobs which have very wide variations in the lengths of haul, and especially if the longer hauls involve considerable quantities, the use of teams is apt to be uneconomical unless the conditions are such that either extra teams can be hired as needed or else that when the shorter hauls are reached the otherwise idle teams can be satisfactorily utilized on wheeler or fresno work.

Some of the difficulties of team hauling, especially for the longer hauls, would no doubt be reduced by a more general use of the 2-cubic-yard three-horse wagons. Where team hauling is used the daily cost of remaining idle may readily reach one half the normal daily operating cost. Consequently, with a team outfit it is generally very important that work be carried on whenever it is at all practicable to do so.

CONCLUSIONS REACHED CONCERNING TRUCK AND TRACTOR OPERATION

Heavy trucks, on the other hand, are apt to prove expensive on very short hauls. Three or five ton trucks are rather generally used in some sections. Where the prevailing hauls are moderate to long and the road, dump, and cut can be suitably maintained, these vehicles give good service. Trucks should be equipped with a quick-acting dumping mechanism which will raise the body to a high angle. Since operating room is restricted on most construction jobs, trucks with a short wheel base are generally found to turn faster both at the dump and the shovel—a very important matter on short-haul work where speed is of but minor importance. On long hauls speed becomes an extremely important element. Yet many jobs have been found where the road conditions were such that the average round-trip speed of the trucks was as low as 300 or 400 feet per minute.

Except where the trucks were equipped with pneumatic tires no job has yet been found where trucks of this class could consistently maintain an average round-trip speed of over 8 miles an hour, or about 700 feet a minute. Generally the speed has been below 6 miles an hour. Where heavy trucks are used more attention to road conditions would be profitable, as would the use of the dual-type pneumatic tires for the rear wheels. Whenever the turning time on short-haul work is long and the operating speed relatively low, the output of the truck can usually be considerably increased by backing the loaded vehicle to the dump and returning it forward to the shovel. Cases have been found where this method proved advantageous up to a haul of over 800 feet. On very short hauls the output of the truck can sometimes be almost doubled in this way.

Bottom-dump wagons of 5 and 6 cubic yards capacity drawn by crawler tractors have been found to be very efficient under a wide variety of conditions. Usually two of these wagons can be drawn by one good 10-ton crawler-type tractor. A good tractor operator can handle one of these trains effectively under conditions encountered in ordinary highway grading work. While the operating speed is rather low—about 275 to 325 feet per minute—the dumping and turning time is low, so that two of these trains can ordinarily handle the full ouput of a ¾-yard shovel up to a haul of from 600 to 800 feet in good common excavation, and to a correspondingly greater distance in material which is more difficult to dig. Each additional train will extend the hauling distance by from 800 to 1,000 feet.

LOADING A TRAIN OF TRACTOR-DRAWN DUMP WAGONS

Where crawler tractors are used to draw large dump wagons, only skilled operators who will take an interest in the work should be employed. Since the number of tractor trains required for the economical operation of the ordinary highway grading job rarely exceeds three, it is very important that they be maintained in proper condition and operated with great regularity.

Power-shovel operation in highway grading work involves a large number of repetitive operations. The dipper must be loaded, swung, and spotted over the hauling unit, the load dumped, and the dipper then returned for another load. From time to time the shovel must be moved forward or maneuvered so as to keep it within easy digging reach of the material. The hauling units must be brought into position and loaded, the load hauled to the dump—at the dump turning and backing is often necessary. The load must then be dumped and the vehicle returned to the cut where turning and maneuvering is frequently necessary

to get into position for receiving another load. As these operations are repeated over and over again throughout the day, it is clear that if a few seconds, or even a fraction of a second, are regularly lost on any one operation, the total loss during the course of the day will be large. If an operator working regularly on a 20-second cycle slows up only just enough to regularly add one second to each of the major operations of loading, swinging, dumping, and returning the dipper, the output will be cut from three to two and one half dippers per minute. Or, if the regular unhampered output is 90 wagonloads per hour, and the drivers of the hauling units slow down so as to delay the shovel only five seconds each time in getting into place to be loaded, then the output will be cut to 80 loads per hour.

Definite stops are, of course obvious and every contractor makes more or less determined efforts to eliminate or reduce them. But a power-shovel outfit may operate all day without a single definite stop and yet not produce more than half the yardage it is capable of producing simply because the management is not aware of the effect on production of the constant loss of seconds or even fractions of seconds in the numerous repetitive operations.

FACTORS AFFECTING THE OPERATING CYCLE

The operating cycle of the power shovel consists of the consecutive actions of (1) loading the dipper, (2) swinging it over the wagon or other hauling unit, (3) dumping it, and (4) swinging it back to loading position. From time to time the shovel must also be moved forward so as to keep within easy digging reach of the face of the cut. This, however, is not a part of the regular operation cycle, but rather a necessary interruption, the relative frequency of which varies principally with the depth of the cut.

Efficiency in power-shovel operation is dependent on the operator and on the shovel itself. A first-class operator may be able to secure fair production with an old or a second-rate shovel, but a poor operator is a heavy handicap even with the very best equipment. It is hoped the records of performance which this series of papers contains may help constructors to increase their present rates of shovel production and the power-shovel manufacturers to so perfect their shovels as to meet still better those conditions which are prerequisite to high rates of production.

It has been stated that under ordinary field conditions the fastest obtainable operating cycle in good common excavation is in the neighborhood of 15 seconds when the swing is 90°. The importance of approaching this limit as closely as possible can hardly be overstated. A 15-second cycle consistently maintained will yield the large output of 240 dipper loads an hour. To attain a 15-second cycle it is necessary to load the dipper regularly in 4 to 5 seconds, to swing it over the wagon in 4 to 5 seconds, to dump it in 1 to 1½ seconds, and return it again to loading position in 4 to 5 seconds. Lengthening the cycle time to 20 seconds drops the output to 180 dipper loads an hour—a reduction of 25 per cent. If the cycle is lengthened to 25 seconds, the best the shovel can turn out is 144 dipper loads an hour, while if a 30-second cycle obtains the output can not exceed 120 dipper loads.

The difference between operation on, let us say, a 15-second cycle and on a 20-second cycle is often a matter of a second or so in loading, a slight hesitation during the swing, with perhaps a bit of delay in spotting over the wagon—delays which may not be noticed except with the aid of extended stop-watch readings. It is not surprising to find that slow operators are sometimes rated as fast because the contractor has nothing definite with which to compare their work and to find that fast operators are sometimes being discredited because job conditions or methods of job management over which they have no control hold down the output.

Examples of the full operating-cycle time where loading was at the side of the shovel are shown in Figures 1 to 5. A detailed analysis of each of the four parts of the operating cycle seems advisable in order to establish more clearly the parts played, respectively, by the operator, the machine, and the material in determining and controlling the rate of production. This will be followed by a somewhat similar analysis of the additional factors affecting production which are more or less completely under the control of the management.

The first activity of the operating cycle is loading the dipper and its effectiveness is dependent on the size of the load and the time taken in securing it. To sacrifice, say, 10 per cent of the size of the dipper load in order to increase the number of dippers by 10 per cent results in a loss in material dug and smaller loads for the hauling units. The smaller the time of loading the dipper as compared with the time of the entire cycle, the greater is the importance of securing a full dipper. It is more important to try for a full dipper when the swing is long than when it is short. In very shallow cuts a low boom will aid in securing a fuller dipper, as will a high boom in a deep cut.

In making these studies determinations have been made as to the number of dipper loads and quantity of material moved under various conditions. Quantities were determined from careful cross-sectioning and are thought to be large enough to represent average conditions. Table 1 gives the results obtained on several jobs. For a so-called ¾-yard bucket having a capacity of approximately three-fourths cubic yard when struck horizontally in line with the top of the teeth and the top of rear edge, the average dipper load may vary from 0.3 to 0.8 cubic yard, depending on the material and the skill of the operator. In fair to good common reasonably free from roots and bowlders, a good operator working under favorable conditions should dig an average of 0.5 or 0.6 cubic yard per dipper load. In poorly blasted rock or shale, very rooty and stumpy soils, and certain tough, moist clays, the average load may be only 0.35 cubic yard or even less in exceptional cases. In shallow cuts the average load is likely to be low. Materials which bulk considerably when broken up or which lack cohesion, and will not heap up on the dipper, are apt to show a low average yield per dipper load.

In general, the largest average dipper load can be secured from cuts of moderate depth, from 5 to 7 feet being perhaps the most advantageous in materials not needing to be blasted. The size of the dipper load is sometimes affected by the position in which the hauling units are loaded. In loose, friable materials which spill

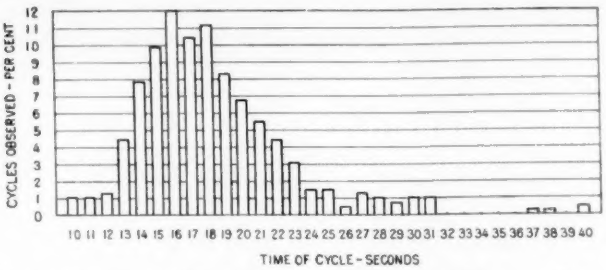


FIG. 1.—DIAGRAM SHOWING PERCENTAGE OF SHOVEL CYCLES PERFORMED IN VARIOUS TIME INTERVALS. BASED ON 383 COMPLETE CYCLES (4 GREATER THAN 40 SECONDS) OF A ¾-YARD SHOVEL WORKING IN AN 8½-FOOT CUT OF BLASTED SHALE AND LOADING TRUCKS AT SIDE. AVERAGE TIME PER CYCLE, 18.9 SECONDS

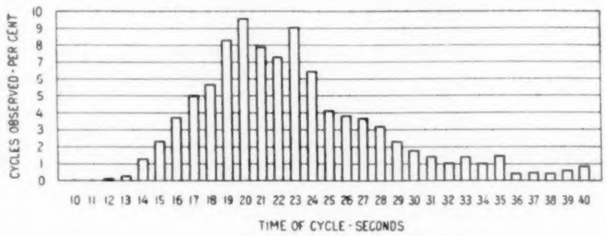


FIG. 2.—DIAGRAM SHOWING PERCENTAGE OF SHOVEL CYCLES PERFORMED IN VARIOUS TIME INTERVALS. BASED ON 1,058 COMPLETE CYCLES (43 WERE OVER 40 SECONDS AND NOT SHOWN) OF A ¾-YARD SHOVEL WORKING IN 1 TO 5 FEET OF A STICKY CLAY AND WITH AN ANGLE OF SWING OF FROM 45° TO 90°. AVERAGE TIME PER CYCLE, 23.9 SECONDS

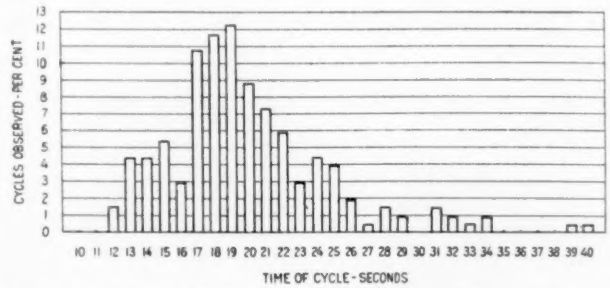


FIG. 3.—DIAGRAM SHOWING PERCENTAGE OF SHOVEL CYCLES PERFORMED IN VARIOUS TIME INTERVALS. BASED ON 204 COMPLETE CYCLES (5 WERE OVER 40 SECONDS AND NOT SHOWN) OF A ¾-YARD SHOVEL WORKING IN FROM 8 INCHES TO 2 FEET OF LOAMY CLAY WITH AN ANGLE OF SWING OF FROM 45° TO 90°. AVERAGE TIME PER CYCLE, 20 SECONDS

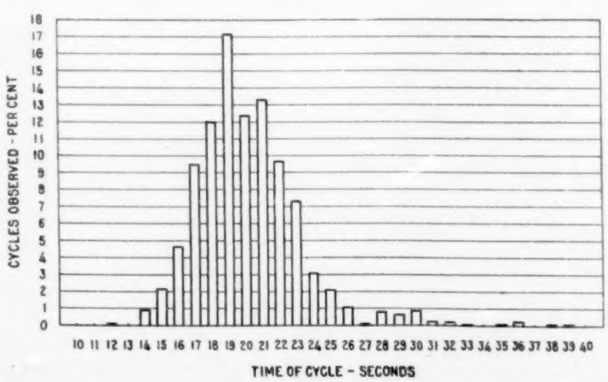


FIG. 4.—DIAGRAM SHOWING PERCENTAGE OF SHOVEL CYCLES PERFORMED IN VARIOUS TIME INTERVALS. BASED ON 734 COMPLETE CYCLES (3 WERE OVER 40 SECONDS AND NOT SHOWN) OF A 1⅛-YARD SHOVEL WORKING IN 2 TO 6 FEET OF CLAY WITH A FEW BOWLDERS. LENGTH OF SWING, 45° TO 90°. AVERAGE TIME PER CYCLE 20.3 SECONDS

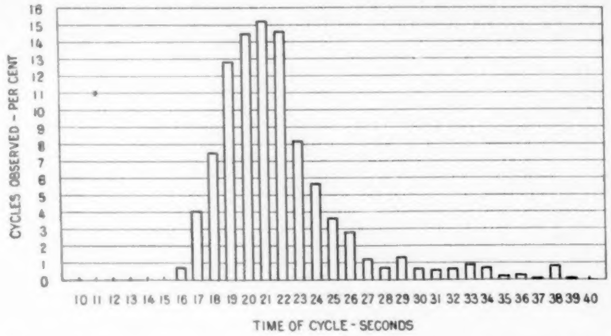


FIG. 5.—DIAGRAM SHOWING PERCENTAGE OF SHOVEL CYCLES PERFORMED IN VARIOUS TIME INTERVALS. BASED ON 1,322 COMPLETE CYCLES (20 WERE OVER 40 SECONDS AND NOT SHOWN) OF A 1⅛-YARD SHOVEL WORKING IN FROM 1 TO 6 FEET OF CLAY WITH A FEW BOWLDERS WITH A SWING OF FROM 45° TO 90°. AVERAGE TIME PER CYCLE, 22 SECONDS

TABLE 1.—*Number of dipper loads and quantity of material moved under various conditions*

Type of shovel	Capacity	Character of material	Quantity moved	Dipper loads	Average loading
	Cu. yds.		*Cu. yds.*	*Number*	*Cu. yds.*
Steam	¾	Light moist clay, free from roots and stones.	57	147	0.39
Do	¾	do	114	223	.51
Do	¾	do	85	170	.50
Do	¾	Light moist clay, with some shale	65	148	.44
Do	¾	Loamy clay, with 25 per cent loose rock	19	50	.38
Do	¾	do	63	156	.40
Do	¾	Sand-clay	49	82	.60
Do	¾	do	93	150	.62
Do	¾	Loamy to hard clay	49	85	.58
Do	¾	Loamy to sandy clay	50	141	.35
Do	¾	Loamy to clay	60	157	.38
Do	¾	do	39	72	.53
Do	¾	Gneiss-granite, poorly blasted	985		.33
Do	¾	Wet sticky clay, with a few stumps	1, 167	1, 745	.67
Do	¾	Moist to wet sand-clay	1, 468	1, 825	.80
Do	¾	Sandstone, well blasted	219	632	.35
Do	¾	do	1, 120	2, 599	.43
Do	¾	Moist clay, with a few small surface bowlders.	518	794	.65
Do	¾	Very wet clay	588	990	.59
Do	¾	Wet clay, with small stumps	100	210	.48
Do	¾	Sandy gravel, with some hard chunks of shale.	1, 683	4, 099	.41
Do	¾	Dry loamy clay	162	309	.53
Do	¾	do	29	71	.41
Do	⅞	Granite-gneiss, poorly blasted	1, 335		.40
Gas	¾	Loamy clay, moist, with a few roots	356	583	.61
Do	1⅛	Sandstone, blasted	1, 840	3, 448	.53
Do	1⅛	Dry clay, with a few bowlders	1, 523	2, 892	.53
Do	1⅛	Dry clay, with surface bowlders	635	996	.64
Do	1⅛	70 per cent large bowlders and 30 per cent dry clay.	381	667	.57
Do	1⅛	10 per cent dry clay, 20 per cent loose rock, 70 per cent solid rock, blasted.	2, 759	4, 384	.63
Do	1⅛	Wet sticky clay, with a few surface bowlders.	1, 364	2, 396	.57
Do	1⅛	20 per cent dry clay, with 80 per cent sandstone, well blasted.	474	784	.60
Steam	¾	Sandy clay and clay loam, with some stone.	1, 555	3, 504	.44
Gas	¾	80 per cent sandstone, poorly blasted, with 20 per cent clay.	363	788	.46
Do	¾	do	3, 010	6, 646	.46

readily, a long swing and especially loading near the limiting height to which the shovel can reach is certain to reduce the amount of material moved per dipper load. Since the rate of operation in materials of this kind should be around 200 dippers an hour, even small differences in the size of the dipper load become important.

Three cases were studied where the contractors in a laudable effort to secure a large yardage per dipper load had replaced regular ¾-yard dippers with 1¼-yard dippers. This proved a decided handicap, except possibly in extremely soft and easy digging, as the power was insufficient to force the large dipper into the material. Not only was the production less than the normal for a regular ¾-cubic yard shovel, but time

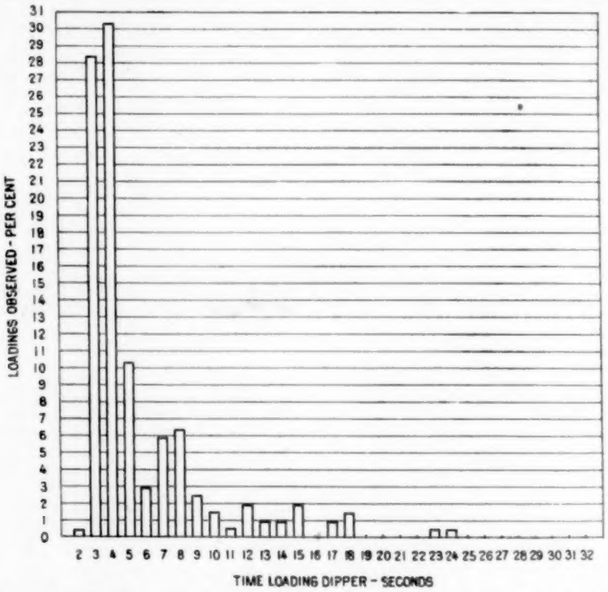


FIG. 6.—DIAGRAM SHOWING PERCENTAGE OF LOADING OPERATIONS PERFORMED IN VARIOUS TIME INTERVALS. BASED ON 204 LOADINGS OF A ¾-YARD DIPPER (3 WERE OVER 32 SECONDS) IN A 1½ TO 2 FOOT CUT OF LOAMY CLAY. AVERAGE TIME, 6.1 SECONDS

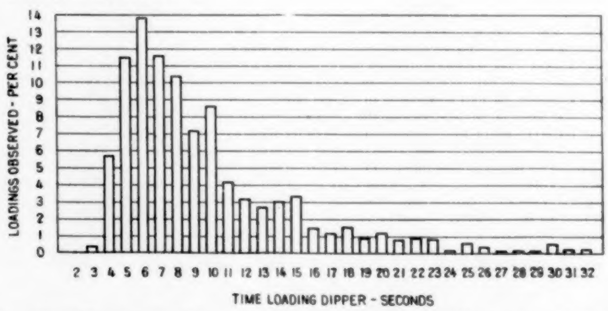


FIG. 7.—DIAGRAM SHOWING PERCENTAGE OF LOADING OPERATIONS PERFORMED IN VARIOUS TIME INTERVALS. BASED ON 1,058 LOADINGS (18 WERE OVER 32 SECONDS) OF A ¾-YARD DIPPER WORKING IN 1 TO 5 FEET OF STICKY CLAY. AVERAGE TIME, 10.29 SECONDS

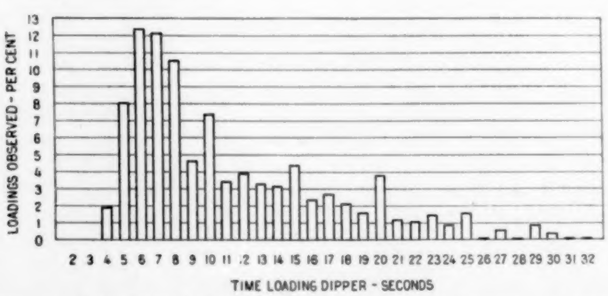


FIG. 8.—DIAGRAM SHOWING PERCENTAGE OF LOADING OPERATIONS PERFORMED IN VARIOUS TIME INTERVALS. BASED ON 658 LOADINGS (16 WERE OVER 32 SECONDS) OF A ¾-YARD SHOVEL WORKING IN 2 TO 6 FEET OF STICKY CLAY. AVERAGE TIME, 12.2 SECONDS

losses due to breakage and repairs were high. This seems to indicate that for general highway work increased production is not to be had by increasing the size of the dipper above that for which the shovel is designed.

The time required to load the dipper often varies considerably from the average, as shown in Figures 6 to 12 and Tables 2 to 4. Each of the graphs shown covers a number of observations and shows the number of times the dipper was loaded in any given number of seconds. They show that a few of the loading times took very much longer than the others and reduced the average very materially.

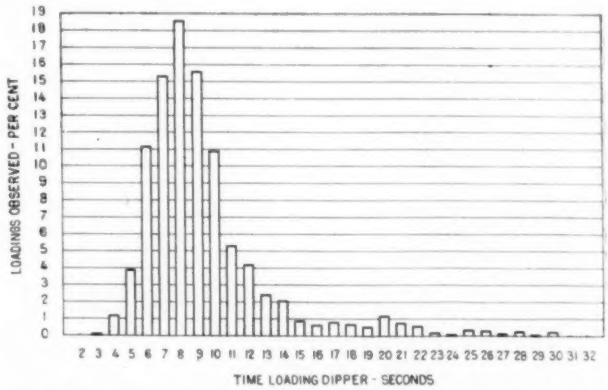


FIG. 9.—DIAGRAM SHOWING PERCENTAGE OF LOADING OPERATIONS PERFORMED IN VARIOUS TIME INTERVALS. BASED ON 1,322 LOADINGS (15 WERE OVER 32 SECONDS) OF A 1⅛-YARD DIPPER WORKING IN 1½ TO 5 FEET OF CLAY AND LOAM WITH A FEW BOWLDERS. AVERAGE TIME, 9.67 SECONDS

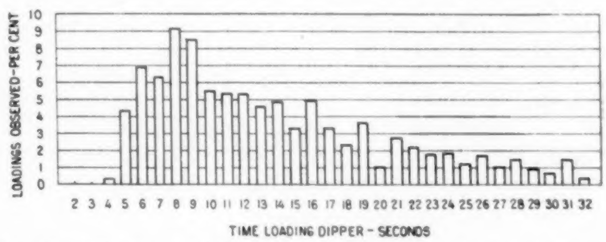


FIG. 10.—DIAGRAM SHOWING PERCENTAGE OF LOADING OPERATIONS PERFORMED IN VARIOUS TIME INTERVALS. BASED ON 763 LOADINGS (21 WERE OVER 32 SECONDS) OF A ¾-YARD DIPPER WORKING IN 1 TO 4½ FEET OF LIGHT LOAM. AVERAGE TIME 16.5 SECONDS

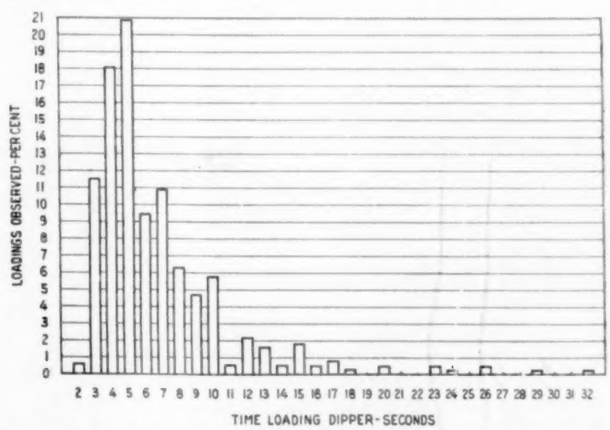


FIG. 11.—DIAGRAM SHOWING PERCENTAGE OF LOADING OPERATIONS PERFORMED IN VARIOUS TIME INTERVALS. BASED ON 383 LOADINGS (6 WERE OVER 32 SECONDS) OF A ¾-YARD DIPPER WORKING IN AN 8 TO 9 FOOT CUT OF BLASTED SHALE. AVERAGE TIME 6.9 SECONDS

Figure 6 shows a job in loamy clay where the performance was excellent. A comparatively large number of dipper loads were secured in four seconds. The average loading time was 6.1 seconds, and there were only a relatively small number of dipper loads which took a long time to secure—an indication that a good, consistent operator was handling the shovel. The

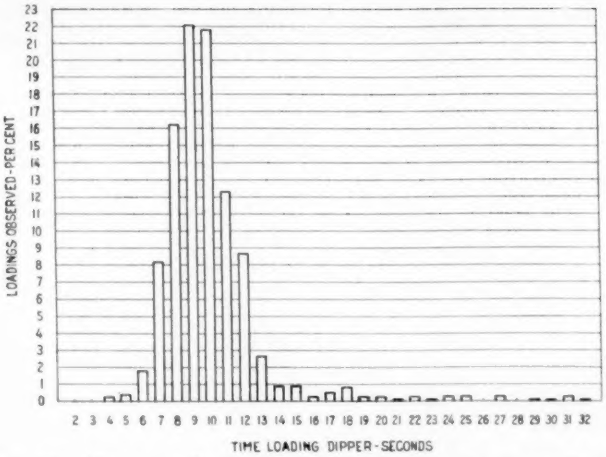


FIG. 12.—DIAGRAM SHOWING PERCENTAGE OF LOADING OPERATIONS PERFORMED IN VARIOUS TIME INTERVALS. BASED ON 734 LOADINGS OF 1⅛-YARD SHOVEL WORKING IN 2½ TO 7 FEET OF CLAY WITH A FEW BOWLDERS

average time during this study for the full cycle of loading, dumping, and return, however, was 20 seconds, since the swing was rather long and the material sufficiently moist to hang somewhat in the dipper.

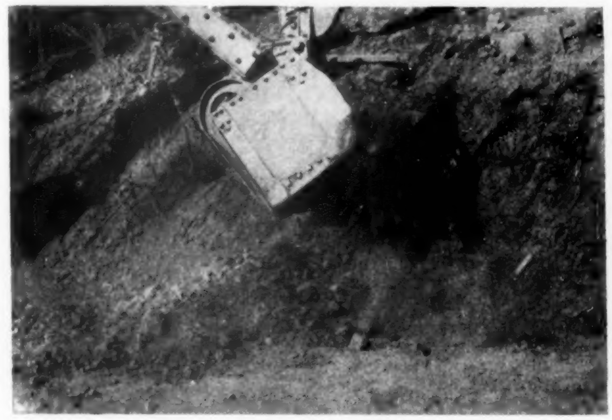
JOB CONDITIONS DETERMINE WHETHER MORE THAN ONE PASS OF DIPPER IS JUSTIFIED

Special attention is drawn to Figures 9 and 11 as examples of good, consistent operation. In the case shown in Figure 8, work was in somewhat sticky clay in which it was hard to secure a full load. In about

LIGHT WORK WHERE MORE THAN THE AVERAGE AMOUNT OF TIME IS REQUIRED TO FILL THE DIPPER

50 per cent of the cases observed, one lift of the dipper was used to secure a load, and in these cases the dipper load was secured in an average of less than seven seconds. In the remaining cases, two or three or even four passes were made to fill the dipper to the satisfaction of the shovel runner. The result was an occasional extension of the time required in filling the dipper to as much as a full minute. The average time for all of the studies was 12.2 seconds. Figures 6, 9, and 12 show the results where the operator regularly made only one pass with the shovel, loading whatever he was able to secure. In these figures are noted the small number of very long readings, and such as occurred were due principally to stumps or heavy rocks.

Table 2 shows the time required in making two or more passes to load the dipper where the shovel was operating in ordinary gravelly clay in moist to wet condition. The average time for loading the dipper when only one pass was necessary was 7.2 seconds. When two passes were required the time rose to 14.1 seconds and to 21.2 seconds for three passes. Thus, each additional pass increased the time required to load the dipper by 95 per cent above the time required where only one pass was necessary.



LOOSE, DRY MATERIAL FALLING FROM TOP OF DIPPER

TABLE 2.—*Time required in making multiple passes in loading dipper in a moist to wet gravelly clay*

Number of passes	Number of observations	Average time per dipper load
		Seconds
1	1,332	7.2
2	298	14.1
3	82	21.2
4	32	27.6
Total or average	1,744	9.4

But production is the product of the number of dipper loads and the average quantity per dipper load. Consequently, the value of making additional passes is dependent on the amount of material which such passes will add to the dipper load and the speed at which the shovel is operating. If a ¾-yard shovel is operating in fairly good common in which the average dipper load is about 0.5 cubic yard of material as measured in place, and the average operating cycle is 20 seconds, then production is at an average rate of 0.025 cubic yard per second. If a second pass to fill an occasional dipper is to be profitable, it must serve to increase the dipper load at least at this rate, for the time required to make the extra pass. Thus, if six seconds are required to make an extra pass under the above conditions, it would not be warranted unless at least 0.15 cubic yard could be added to the load. In other words, whenever the first pass secured as much as three-fourths of an average dipper load a second pass would not be warranted, considering the case from the viewpoint of shovel output alone.

NOT POSSIBLE TO FORMULATE DEFINITE RULES OF PROCEDURE

Definite rules can not be formulated since each operation is interrelated with many other possible conditions surrounding the entire job. It is possible to show the principles which apply and by means of which the proper procedure can be determined. It has been stated that the importance of securing a full

dipper load is greatest when the time required to load the dipper is in smallest ratio to the total shovel cycle, and vice versa. Therefore, more attention to securing a large dipper load is justified when loading at the rear of the shovel than when the loading is at the side. In shallow cuts, where much skimming is required, dipper loads are almost certain to average a low quantity. Keeping the boom lower than normal will generally help in securing larger loads. On such work a considerable amount of time is consumed in moving the shovel. If there is any considerable amount of it, the contractor may well consider the advisibility of using some other method on such portion of the work.

It is not possible to state categorically that any one system of operation is always to be preferred. In the case illustrated by Figure 8 the swing was long and there was not enough hauling equipment on the job; so lengthening the dipper cycle in order to secure a full dipper load did not, in fact, subtract much from the shovel output, while it tended to insure a full wagonload every trip which increased the job output. In the cases shown in Figures 9 and 12 the shovel was a 1⅛-yard machine and two full dippers overloaded the wagons. As long as the operator could get one full dipper load out of two, he could send the wagons to the dump well loaded without making multiple passes. On this job the wagon supply, generally speaking, was above average so that fast operation was desirable.

But, aside from the conditions prevailing on these two jobs and the rates attained, these two figures show several of the general characteristics of what, under normal working conditions, would be good operation and poor operation. A good operator working in anything like good material under favorable conditions of depth and face of cut obtains a loading diagram for his dipper like those in Figures 6, 9, and 12. A poor operator always has an operating record more or less like those in Figures 8 and 10. On the jobs represented by the first set of graphs the shovel was so handled that the desired load was obtained quickly with one pass of the shovel. On the jobs represented by the second set the rate was slower, and frequently two, three, or more passes were made to fill the shovel.

SLOW LOADING MAY BE CAUSED BY SEVERAL FACTORS

The position of the shovel with reference to the face of cut is in no small degree responsible for the repeated passes some shovel runners make in filling the dipper. The dipper is actuated by two separate and distinct motions—one, known as the "hoist," tends to raise the dipper in a vertical circle about the point of intersection of the boom and the dipper stick, while the other, known as the "crowd," controls the length of the radius of the arc in which the "hoist" moves the dipper. In loading, the "crowd" is used to force the dipper against the face of the cut, and on the swing to spot the dipper correctly over the hauling unit. When the dipper stick is in a vertical position the combined motion of the "crowd" and the "hoist" can drive the cutting edge of the dipper almost straight forward several feet, and when the dipper stick is horizontal the crowd serves to hold the cutting edge of the dipper hard into the bank.

When loading the dipper from a bank less than 2 feet high, direct thrust forward into the bank is required, while on a bank 6 or more feet high the loading is generally best done by a longer swinging motion in which a comparatively thin slice is cut from the bank. For some reason it appears to be difficult to find operators who will perform both operations equally well. To make the shovel function smoothly where the bank is low, it must stand close to the bank with the boom somewhat lower than normal and must be moved forward frequently. This is because the forward thrust of the dipper resulting from the proper combination of the "hoist" and "crowd" only reaches a relatively short distance. Cutting from a high bank is best done after the dipper has begun to turn definitely upward in its swing, which requires that the shovel should stand well back from the bank with the boom high. The superintendent who will watch this matter closely and drill his shovel runners in the proper positioning of the shovel for effective dipper loading will find the results gratifying.

In addition to these causes of slow loading, viz, poor handling of the dipper itself and improper position of the shovel with reference to the face of the cut, the material itself is responsible for a good deal of slow digging. Banks composed of good-sized rocks embedded in a stiff clay are particularly troublesome. The runner can not see such rocks, and when the dipper strikes one it may be necessary to draw back and try again. Often two or three passes must be made—sometimes twice that many—before either a load of loose material is secured or the exact position of the rock defined so that it can be picked up.

Tables 3 and 4 show something of the effect of the material on the time required for filling the dipper. Table 3 contains a few good illustrations of fast work in good common by shovel No. 1. A comparison of these tables will give a very fair impression of the difference between work in good ground and work in difficult material. They do not show the quantities moved, but, in general, fast operation in good material was accompanied by large dipper loads and the quantity decreased with difficulty in loading as indicated by the time factor.

TABLE 3.—*Effect of material on time required to load a ¾-yard dipper as indicated by one-hour stop-watch studies with same operator throughout on each shovel*

SHOVEL NO. 1

Kind and character of material	Time to load dipper	Height face
	Seconds	*Feet*
Light sandy loam, free from roots and stones	3.3	10.0
Do	3.3	7.0
Loamy clay, free from roots and stones	4.5	6.5
Do.	4.7	6.0
Do	4.8	10.0
Light clay and loam top soil, no roots or stones	4.9	2.0
Light clay with small amount of soft shale	5.0	5.0
Loam	5.3	5.0
Light clay, free from roots and stones	5.6	10.0
Light clay with small amount of shale	5.7	10.0
Do	5.8	4.0
Light clay with increasing amount of shale	5.9	7.0
Loamy clay, with some roots	6.0	6.5
Ordinary clay, free from roots and stones	6.2	4.5
Loamy clay	6.5	0.3-1.5
Light clay and soft shale	6.6	8.0
Loamy clay with loose rock in old roadbed	8.2	2.0
Clay with 50 per cent loose shale	10.7	6.5
Hard clay with loose rock in old roadbed	15.9	0.25-2.5
Hard clay with loose rock	16.3	2.0
SHOVEL NO. 2		
Light, loamy clay, no stones or roots	5.2	5.5
Do	5.3	4.0
Light clay, free from stones or roots	5.7	4.0
Light clay, practically free from roots and stones	6.0	3.5
Light clay with old hard roadbed on one side	6.7	6.0
Do	6.9	4.0
Light to medium clay	7.5	4.5
Clay and soft shale	8.2	2.0
Light clay with small amount of rock, side hill cut	9.2	0-4.0
Clay and soft shale	9.4	7.0
Sandstone, soft enough to crumble in hand	11.0	11.0

TABLE 4.—*Time required to load dipper in various kinds of material. Each entry shows the number of one-hour studies in which the average time of loading fell within the range indicated. Studies were made on a great many typical jobs*

Average time to load dipper (seconds)	Loam, loamy, sandy, gravelly, or friable materials, practically free from roots, bowlders, etc.	Ordinary clays, ordinary soils, and friable materials with few roots or loose rock, etc.	Fairly hard or tough clays, ordinary clay with some loose rock, shale, etc.	Mixtures of clay and loose rock, soft shale, and hard and tough clays, etc.	Well-blasted rock, shale, etc.	Fairly well blasted rock, loose rock and bowlders, hard or tough clay with rocks, etc.	Clay-gravel in 6 to 9 foot cut with 2 feet of hard frost on surface.	Poorly blasted rock or shale, bowlders, hardpan, etc.
3 to 4	1							
4 to 5	7							
5 to 6	18							
6 to 7	2	18						
7 to 8		12						
8 to 9		5	11					
9 to 10			13		6			
10 to 11			26	6	2			
11 to 12				21	4			
12 to 13				11	9			
13 to 14				7	5		3	
14 to 15					9		2	
15 to 16					3	4	1	
16 to 17					2	7	1	
17 to 18						10		1
18 to 19						7	4	
19 to 20						6		3
20 to 22						1	2	9
22 to 24								3
24 to 26							1	7
26 to 28								4
28 to 30								1
30 to 35								
35 to 40								2
Average time of loading in seconds	5.2	7.1	9.7	11.9	12.4	17.6	17.4	23.9

LARGE ANGLE OF SWING CAUSES CONSIDERABLE TIME LOSSES

Figures 13 to 15 show the time consumed in making the swing and returning the dipper for various angles of swing on three jobs. Under perfect operating conditions curves showing the rate of swing would probably be straight lines except for the influence of acceleration. That the points for one set of final observations do not all fall on the same line is due to the fallibillity of the operator and the many other factors influencing performance; each individual swing ordinarily being subjected to a set of conditions different in some particular from the others.

The curves have not been projected to intercept the x-axis, since measurements were not made of the time loss in accelerating the dipper, but inspection of these and other graphs not shown indicates that the x-intercept or lag in getting the dipper started on the swing is variable for different shovels. It appears that the types of shovels with a slow-swing speed have a shorter lag, so that the actual time required for the swing and return, as shown in Table 5, is often as short or shorter for the slow-speed types so long as the angle of swing is small, but on the longer swings the higher speed types are considerably faster. Figures 16, 17, and 18 also show the variations found in the swing and return time under actual field operation.

The portion of the swing and return time which has here, for want of a better term, been designated as the "lag" is evidently the sum of two or more factors. Time is required for the operator to react and manipulate the necessary mechanism, and it is also required to accelerate the shovel and its load

TABLE 5.—*Comparison of combined swing and return time for various types of power shovels*

[The values are averages from field studies under ordinary operating conditions]

Angle of swing	Gas shovel	Steam shovel	Gas and air shovel	Gas shovel
	Seconds	*Seconds*	*Seconds*	*Seconds*
30°	8.2	8.0	8.2	5.7
60°	10.4	9.0	9.9	8.4
90°	12.5	10.0	11.5	11.2
120°	14.6	11.0	13.2	13.9
180°	19.0	12.9	16.5	19.3
240°	23.4	14.9	19.8	24.8
270°	25.5	15.9	21.5	27.5

HANDLING DIFFICULT MATERIAL GREATLY INCREASES THE CYCLE TIME

from rest and again to decelerate it at the end of the swing. While it is very difficult to separate the lag into its purely personal and mechanical factors, the studies show very conclusively that the personal element involved is sufficiently large to warrant careful consideration because of its effect on the rate of production. For a good operator these reaction lags are small—generally less than one second. For a slow operator they will run twice this or even more. The difference of one or two seconds seems like a trifling matter, but the use of an operator who, because of these losses, takes 18 seconds where only 15 are necessary, reduces the rate of production almost 17 per cent. To change an operator making a load every 18 seconds for a man who takes 20 seconds reduces the rate of output about 10 per cent. With a good wagon supply and production running at a high rate, this can easily reduce the value of the output secured from \$20 to \$25 a day—about twice the ordinary wages of a first-class operator. It never pays to hire cheap, poorly trained operators on any sort of work requiring fast, uniform, consistent operation, and there is no point in highway work where this is more true than on power shovels.

Reverting to the swing itself and starting with the 90° swing (loading at the side of the shovel) which in good common and under favorable conditions can be done in 15 seconds, an extension of the swing to 180° (loading back of the shovel) extends the cycle by from three to eight seconds, depending on the type of shovel used and the skill of the operator. As a general average it may be said that loading behind the shovel extends a 15-second cycle to 20 seconds, and by so doing reduces the attainable rate of output 25 per cent.

There is much work where loading at the side of the shovel is impossible, largely because of narrow cuts. Deep cuts sometimes make loading at the side impossible if the whole cut is taken out at one operation. In general, however, there are many more situations where side loading could be practiced than are now utilized. Many contractors apparently feel that there are so many places where side loading can not be done that nothing substantial can be gained by training their men to utilize such opportunities as occur. The advantage of such methods depends largely on the available supply of transportation which will be discussed in a following article.

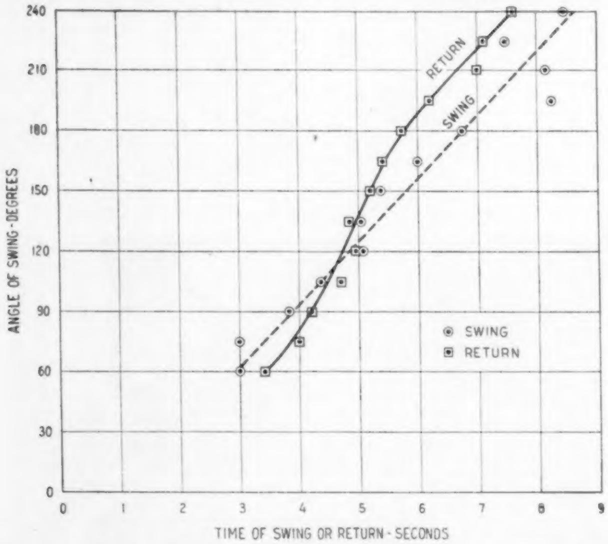


FIG. 13.—INFLUENCE OF ANGLE OF SWING ON TIME OF SWING AND RETURN BASED ON 506 OPERATIONS OF A 3/4-YARD SHOVEL HANDLING POORLY BLASTED ROCK. NOTE THAT THE POINTS LOCATED FOR TIME OF SWING ARE MUCH MORE IRREGULAR THAN THOSE FOR TIME OF RETURN. THIS IS EXPLAINED IN PART BY THE EXTRA CARE REQUIRED IN HANDLING BOWLDERS. AVERAGE RATE OF SWING 32° PER SECOND. AVERAGE RATE OF RETURN 46° PER SECOND

A FULL DIPPER LOAD BEING SPOTTED FOR DUMPING

Extending the average swing to 270° is unqualifiedly objectionable and especially so where slow-swing shovels are used. This extends the cycle to 25 or more seconds and correspondingly reduces the rate of output. Such operation may be caused by a cab arrangement where it is hard for the operator to see out of one side of it. To avoid swinging his load over objects he can not see clearly and running the risk of dropping material on men or animals he can not see, the longer swing is sometimes used. Poor vision also interferes with spotting the dipper exactly before dropping the load. Hauling units are usually placed for a swing from one side. This is important if rock is being handled, for while a good operator seldom drops any material it takes very little to seriously injure a man or an animal. As a general rule, it may be said that an average swing of much over 180° is the result of improper equipment or faulty operating methods, but that occasions may arise when it is better to make a few 270° swings than to change the loading position of the hauling equipment.

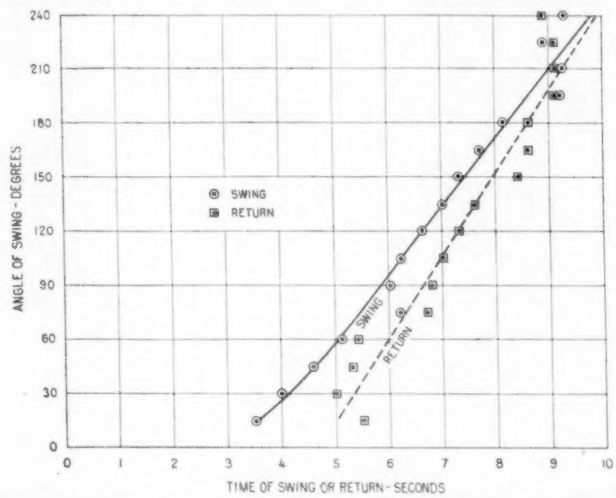


FIG. 14.—INFLUENCE OF ANGLE OF SWING ON TIME OF SWING AND RETURN BASED ON 2,069 OPERATIONS OF A 3/4-YARD SHOVEL WORKING IN CLAYEY GRAVEL. AVERAGE RATE OF SWING 37.5° PER SECOND. AVERAGE RATE OF RETURN 46° PER SECOND

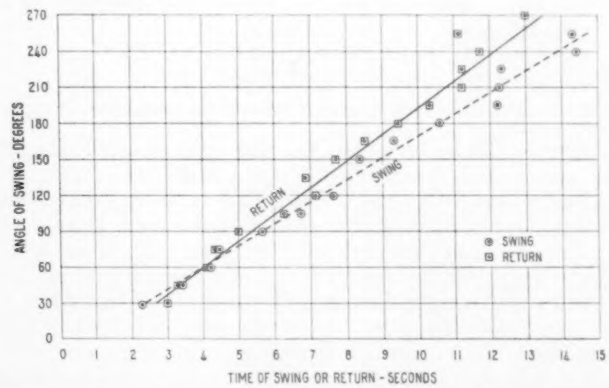


FIG. 15.—INFLUENCE OF ANGLE OF SWING ON TIME OF SWING AND RETURN, BASED ON 1,788 OPERATIONS OF A 3/4-YARD SHOVEL WORKING IN GRAVEL AND LOOSE AND BLASTED SHALE. AVERAGE RATE OF SWING, 18° PER SECOND. AVERAGE RATE OF RETURN, 22° PER SECOND

Table 6 shows the average time used in loading, swinging, dumping, and returning the dipper for several jobs where the swing ranged from 30° to 270° and when the swing was 90° or less. It is apparent that when the point of loading and the point of dumping are within the operator's vision at the same time he can keep his mind far enough ahead of his work so that his general reactions are faster and all of his operations are conducted with more confidence. As he digs his load he determines where he will dump and the manipulations necessary in the process. As he drops it he determines where he will get the next bite, and so on. The saving in time is small per load, but it is enough to make considerable difference in the day's run.

TABLE 6.—*Time required to load, swing, dump, and return shovel on various jobs where the swing varied from 30° to 270° and on the same jobs where it did not exceed 90°*

Shovel	Readings	Load	Swing	Dump	Return	Total cycle
	Number	*Seconds*	*Seconds*	*Seconds*	*Seconds*	*Seconds*
ANGLES OF SWING FROM 30° TO 270°						
Type A, Delaware County, N. Y.	2,033	12.8	4.6	2.7	4.2	24.3
Do	1,788	12.7	8.3	4.0	7.5	32.5
Type B, Pike County, Pa	2,642	9.7	6.1	3.3	6.3	25.4
Type C, Pike County, Pa	2,069	10.0	7.1	4.4	7.6	29.1
Type D, Columbia County, N. Y	868	10.3	5.3	3.5	5.4	24.5
Type E, Hughes County, Okla	1,734	9.4	4.5	2.1	5.5	21.5
ANGLES OF SWING 90° OR LESS						
Type A, Delaware County, N. Y.	1,781	11.9	4.2	2.3	3.8	22.2
Do	645	13.6	4.2	3.0	4.1	24.9
Type B, Pike County, Pa	1,625	8.9	4.6	2.9	5.2	21.6
Type C, Pike County, Pa	634	10.0	5.3	3.5	5.9	24.7
Type D, Columbia County, N. Y	548	10.0	3.9	3.2	3.8	20.9
Type E, Hughes County, Okla	1,677	9.3	4.4	2.1	5.4	21.2

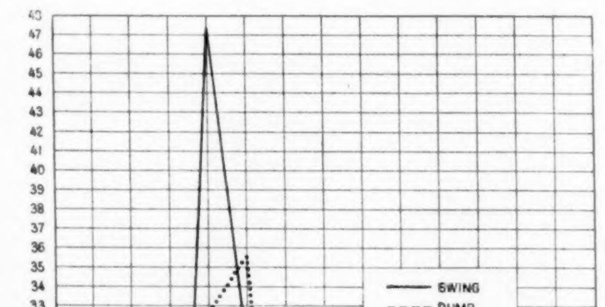


FIG. 16.—PERCENTAGE OF OPERATIONS OF SWINGING, DUMPING, AND RETURNING PERFORMED IN VARIOUS TIME INTERVALS.[1] BASED ON 1,058 CYCLES OF A ¾-YARD SHOVEL WORKING IN STICKY CLAY WITH AN ANGLE OF SWING OF FROM 45° TO 90°. AVERAGE TIME OF SWING 4.42 SECONDS. AVERAGE TIME OF DUMPING, 4.31 SECONDS. AVERAGE TIME OF RETURN, 4.86 SECONDS

[1] Each of these curves (figs. 16 to 19) is in reality formed from the sum of a number of superimposed curves having the general form of the skewed probability curve, but in the interest of clearness the points from actual field readings have been connected by straight lines.

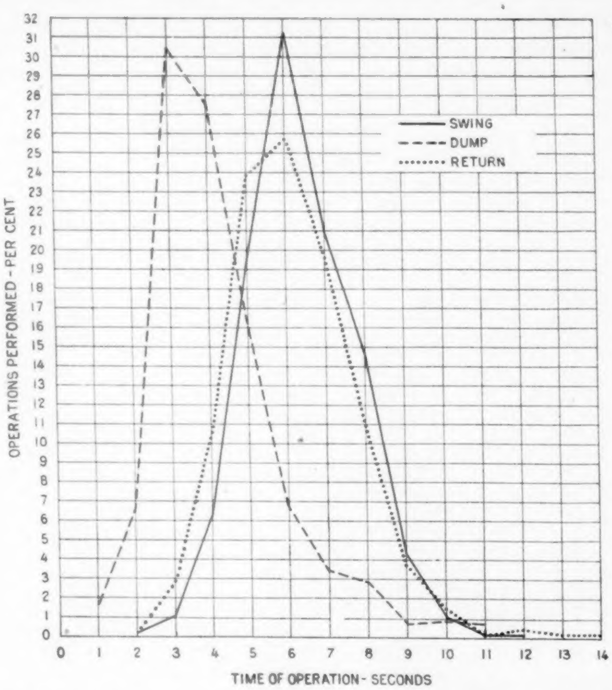


FIG. 17.—PERCENTAGE OF OPERATIONS OF SWINGING, DUMPING, AND RETURNING PERFORMED IN VARIOUS TIME INTERVALS.[1] BASED ON 658 CYCLES OF A ¾-YARD SHOVEL WORKING IN STICKY CLAY WITH AN ANGLE OF SWING OF FROM 150° TO 180°. AVERAGE TIME OF SWING, 6.23 SECONDS. AVERAGE TIME OF DUMPING 4.33 SECONDS. AVERAGE TIME OF RETURN 6.10 SECONDS

DUMPING THE DIPPER

The next item in the list going to make up the full cycle is discharging the load. This is an operation which requires great skill if it is to be done rapidly. The load must not be dropped from too great a height or the wagon will be damaged, and it must not be dropped too soon or too late or much of it will fall outside of the wagon. If the load is composed of loose common—light loam, sand, loamy clay, or rather fine gravel—an experienced shovel runner will drop it just as the swing ends and be ready to start the return as soon as the dipper comes to a stop. In such material the fast operator really takes no time to drop the load, the time consumed being only that needed to stop the dipper and then start it on the return swing, and this can be done regularly in one second. Wet, sticky clays and other adhesive materials often require considerable shaking or jarring to get them out of the dipper. The time required depends on the skill of the operator but more largely on the average amount of shaking and jarring necessary to get them out of the dipper. It is not unusual to find dumping time in sticky materials regularly running as high as five or six seconds, though it necessarily varies with the degree of adhesiveness of the material. Considerable care must be taken by the operator to prevent injury to the wagons or trucks, which naturally slows down the rate of operation and large chunks often hang or wedge in the dipper and require manipulation to release them. Roots and stumps are often very troublesome in this respect.

Table 7 shows how the average dumping time is affected by the kind and character of the materials found from one-hour stop-watch studies. Figures 16, 17, and 18 show the time used in dumping material

from the dipper into the wagons or trucks under typical conditions. Figure 19 shows the average dumping time for a number of classes of material as found from the analysis of 10,200 readings secured on 13 different

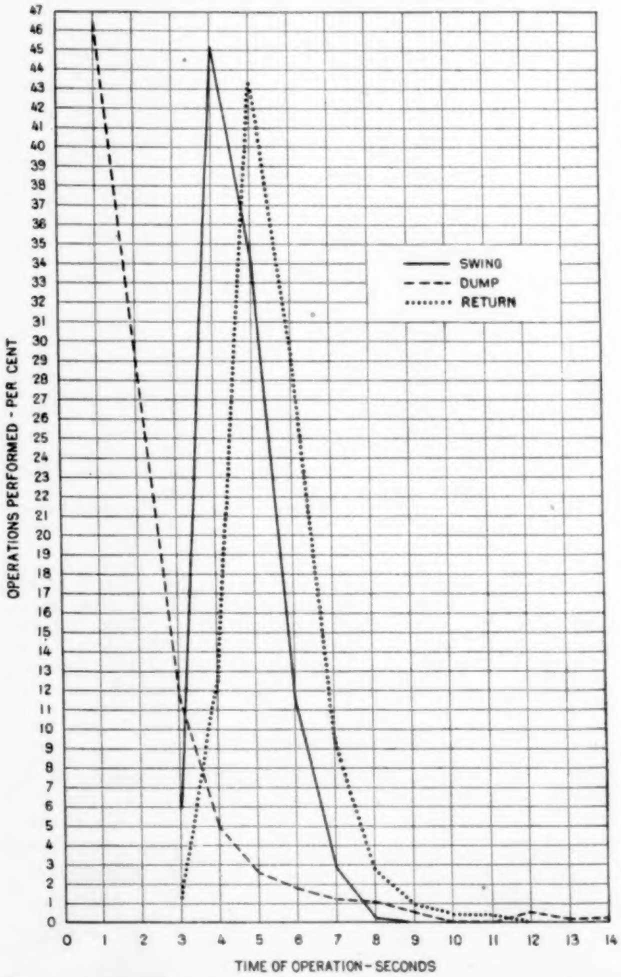


FIG. 18.—PERCENTAGE OF OPERATIONS OF SWINGING, DUMPING, AND RETURNING PERFORMED IN VARIOUS TIME INTERVALS. BASED ON 1,322 CYCLES OF A 1⅛-YARD SHOVEL WORKING IN CLAY WITH SOME BOWLDERS WITH AN ANGLE OF SWING VARYING FROM 45° TO 90°. AVERAGE TIME OF SWING, 4.62 SECONDS. AVERAGE TIME OF DUMPING, 2.23 SECONDS. AVERAGE TIME OF RETURN 5.49 SECONDS

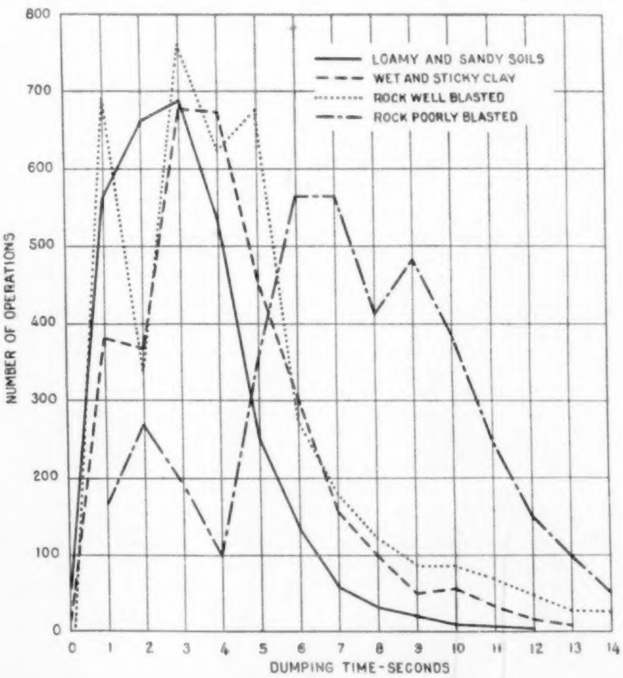
jobs with various grades of operators and six different makes of shovels. It will be noted that a considerable percentage of the operations were performed very rapidly.

CRAWLER-TRACTION SHOVELS HAVE BIG ADVANTAGE IN SPEED OF MOVEMENT

The movement of the shovel within the cut to keep within easy reach of the face constitutes a definite limitation to uninterrupted repetition of the dipper cycle and is a check on production which can not be entirely removed. The best that can be done is to train the operator to make these moves as expeditiously as possible. In deep cuts the time required is small, generally less than 1 per cent, where shovels with the latest crawler-type traction are used. In shallow cuts, however, the proportion mounts very rapidly and cases where 8 to 10 per cent of the total time is used in moving the shovel are not uncommon,

TABLE 7.—*Effect of character of material on time required to load and dump dipper*

Character of material	Observations	Time to dump dipper	Time to load dipper
	Number	*Seconds*	*Seconds*
Loam and light clay	722	1.0	4.2
Do	351	1.5	5.4
Loamy clay and soft shale	254	1.9	5.4
Soft shale	399	4.2	6.5
Sandy clay	249	3.0	7.4
Moist clay	96	2.4	8.0
Light clay, wet and gummy	173	4.6	8.1
Clay and surface loam	692	1.9	8.4
Sandy clay, moist to wet	349	4.8	8.8
Well blasted sandstone with 20 per cent light clay	229	1.8	9.3
Clay with a few bowlders	448	2.1	10.0
Heavy clay, wet and gummy	271	5.3	10.4
Clay with some surface bowlders	2,892	1.8	10.5
Loam with loose rock and loose shale	369	2.8	10.5
Do	288	2.4	11.8
Clay-gravel	506	1.7	11.8
Heavy clay, wet and sticky	83	6.0	12.0
75 per cent loose shale with 25 per cent clay	579	3.2	12.4
Heavy clay with a few bowlders	101	2.0	12.5
Wet clay with some stumps	105	3.2	12.8
Loam with 30 per cent loose rock	148	2.1	13.5
Rock, well blasted	183	3.4	13.9
Do	560	4.2	15.1
Hard shale, well blasted	1,434	2.6	16.4
Gneiss, poorly blasted	550	10.7	18.5
50 per cent loose rock with 50 per cent unblasted shale rock	338	-------	28.0



Average dumping time

Loamy and sandy soils	seconds	2.9
Wet and sticky clay	do	4.0
Rock, well blasted	do	4.4
Rock, poorly blasted	do	8.9

FIG. 19.—NUMBER OF DUMPING OPERATIONS PERFORMED IN VARIOUS TIME INTERVALS IN DIFFERENT KINDS OF MATERIAL. BASED ON 10,200 OBSERVATIONS ON 13 DIFFERENT JOBS

especially where the operator is slow or where the mechanism is in poor condition. Because of the general prevalence of insufficient hauling equipment it has become a more or less accepted practice to consider the time required for moving the shovel as of no importance, since it can usually be done while waiting for teams or trucks. This may seem like a good way of neutralizing an inherent shortcoming of the shovel,

(Continued on p. 274)

COMPARATIVE TESTS OF CRUSHED-STONE AND GRAVEL CONCRETE IN NEW JERSEY

REPORT ON COOPERATIVE TESTS CONDUCTED BY THE NEW JERSEY STATE HIGHWAY COMMISSION AND THE U. S. BUREAU OF PUBLIC ROADS

Reported by F. H. JACKSON, Engineer of Tests, Division of Tests, U. S. Bureau of Public Roads

DURING the summer of 1926 the New Jersey State Highway Commission, working in cooperation with the Bureau of Public Roads, conducted a series of concrete tests at the Trenton laboratory of the commission, for the purpose of determining the relative quality and economy of concrete paving mixtures in which 13 different gradations of crushed stone (trap) and gravel were used as coarse aggregate. The investigation involved the making and testing of approximately 150 concrete beams, 8 by 8 by 48 inches in size and 250 concrete cylinders 6 by 12 inches in size.

This report describes in order (1) the various reasons which led up to the investigation, (2) the procedure followed, (3) the results secured, and (4) the conclusions reached, and makes certain recommendations relative to the application of these results. It should be borne in mind that this series of tests was initiated for the purpose of studying the relative merits of two different types of coarse aggregate produced under certain conditions. The results can therefore be considered as applicable only to the same kinds of material, produced in a similar manner. In order to make possible the drawing of more general conclusions as to the effect of type and gradation of coarse aggregate upon the quality of concrete a series of tests has been started at the Arlington laboratory of the bureau. These tests are similar to those described here but involve seventeen types of coarse aggregate instead of two. It is anticipated that conclusions suitable for general application will be justified by these tests, but in the meantime those presented here should not be considered as having any application beyond the particular conditions involved.

THE CONCLUSIONS drawn from these tests should not be interpreted as indicating that crushed stone as a type is superior to gravel as coarse aggregate for cement concrete pavements, but only as indicating that for the particular conditions and kinds of materials involved, concrete in which crushed trap rock was used showed an average flexural strength approximately 12 per cent higher than similar concrete in which gravel was used.

Tests now in progress at the Arlington Laboratory using 17 different coarse aggregates give preliminary indications that materials similar to those used in this investigation will give similar results, but also that the characteristics of the particular aggregate used may be fully as important as the type of material to which it belongs.

REASONS LEADING TO INVESTIGATION DISCUSSED

The practice followed in New Jersey and most other States of specifying the same proportions of cement and graded aggregate for concrete, regardless of the void content of these aggregates, has resulted in securing for gravel aggregate an appreciable economic advantage due to the increased yield of concrete obtained from the gravel aggregate on account of its low void content, as well as its lower cost compared with that of crushed stone. These facts, together with the other natural advantages possessed by gravel, such as the increased workability of the resulting concrete, have made its use in general more economical than crushed stone.

Such a condition would not in itself warrant any change in the existing methods of proportioning. It must be remembered, however, that the arbitrary proportions which are set are only a means to an end which, in this case, is the production of concrete possessing certain definite essential physical properties. If a specification is to be considered adequate it must be assumed that, as long as the various details of the specifications relative to materials and construction processes are complied with, concrete of substantially uniform quality will be obtained; in other words, that any variation in either type or gradation of aggregate within the specification limits will not result in any essential change in the quality of the product.

The standard road specifications of the New Jersey Highway Commission require that concrete for pavements shall be mixed in the proportions of 1 part cement to 1¾ parts sand and 3½ parts coarse aggregate by volume measured in a loose, dry condition. In the determination of the field mix, the amount of sand is proportioned on a dry, loose basis; that is, a bulking correction is made. Either crushed rock or gravel conforming to certain requirements as to quality and gradation may be used. This, as has been pointed out, results in the production of more concrete per unit volume of cement when gravel is used as coarse aggregate than when stone is used, due of course, to the higher void content of the crushed stone aggregate.

It has been repeatedly urged by the crushed-stone interests in New Jersey that concrete produced from crushed stone is of a better quality than that produced from gravel due to the difference in character of these two aggregates and to the higher cement content of the stone concrete, as expressed in terms of volume of cement required to produce a unit volume of concrete.

If these claims are true, they are of considerable significance, because it means that, if the gravel concrete produced under the present specifications is satisfactory in quality, the use of crushed stone results in the production of a higher quality of concrete than is demanded by the minimum requirements of the specifications. If, on the other hand, the crushed-stone concrete is no better than it should be, the obvious conclusion is that the gravel concrete will not meet the minimum requirements. In either event, if it is shown that the type of aggregate does affect the quality of the concrete to an appreciable degree, some readjustment should

be permitted in order to insure concrete of equal quality irrespective of the type of aggregate used.

SCOPE OF TESTS AND MATERIALS DESCRIBED

Recognizing the importance of this problem from both the engineering and economic points of view, the Bureau of Public Roads and the New Jersey State Highway Commission undertook a study of the question through a series of carefully controlled laboratory tests to determine the following:

1. The relative strength and yield of crushed-stone and gravel concrete of the same proportions and consistency, and with the same size and grading of coarse aggregate.
2. What grading of coarse aggregate and what proportions of fine to coarse would give the greatest yield for each type of aggregate, when the concrete is designed for a given strength.

In discussing the essential characteristics of paving concrete, it is herein assumed that in so far as strength is concerned, resistance to bending or flexure is of more significance than is resistance to crushing. Many engineers, in designing concrete pavements, employ the flexural strength of the concrete in calculations for edge and center thickness of slabs under given conditions of load and accept it as the criterion of quality rather than the compressive strength. It is obvious, therefore, that factors influencing flexural strength are of critical importance in so far as pavement concrete is concerned.

To secure flexural-strength tests that would not be unduly influenced by the size of the aggregates used, it was decided to make the major strength comparisons from the results secured with concrete beams 8 by 8 by 48 inches in size, tested as cantilevers for flexural strength using a device similar to that described by Clemmer in Public Roads for May, 1926. It was also decided to use the ends of the beams from the flexure tests as compression specimens in determining the crushing strength of the concrete as well as the 6 by 12 inch cylinders which were cast for this particular purpose. Tests were to be made on all specimens at the age of 28 days, as well as additional series of tests on the $1:1\frac{3}{4}:3\frac{1}{2}$ specimens at the age of six months. Accurate measurements of the yield of concrete obtained from each batch were also to be taken.

Thirteen gradations of crushed trap rock and gravel were employed, ranging from a 3-inch maximum down to a 1-inch maximum size. Well-graded and poorly graded combinations were used, the object being to cover quite a wide range of coarse-aggregate gradations within these limits. The exact screen analysis of each combination is shown in Table 1 and is plotted graphically in Figures 1 and 2, which also show the present New Jersey State requirements for crushed stone for concrete pavements. State requirements for gravel for concrete are similar to those for crushed stone except that more material finer than one-half inch is permitted in the gravel than the crushed stone. For convenience in visualising the gradings of the coarse aggregate, the fineness modulus of each combination was calculated and is shown in Table 2, together with the "maximum size," a value to be used in connection with any design calculations which might be made by the fineness-modulus method. This table also shows the percentage of fine aggregate required by the fineness-modulus method for each gradation calculated on the basis of the sand employed in these tests.

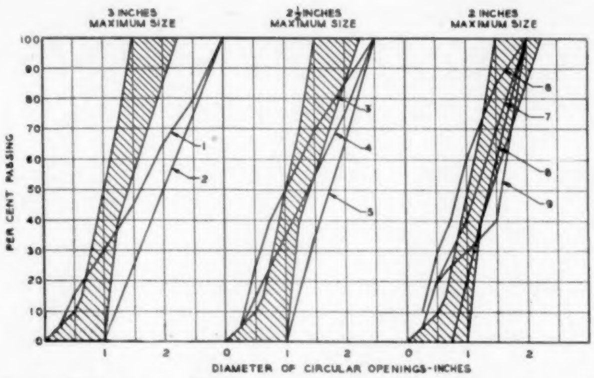


FIG. 1.—RELATION BETWEEN AGGREGATE GRADINGS AND STATE SPECIFICATIONS FOR SIZE OF CRUSHED STONE. AREAS CROSS HATCHED INDICATE SPECIFICATION LIMITS

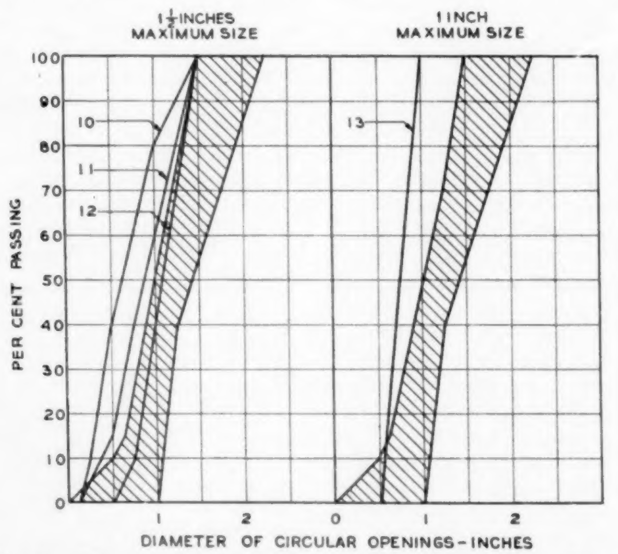


FIG. 2.—RELATION BETWEEN AGGREGATE GRADINGS AND STATE SPECIFICATION FOR SIZE OF CRUSHED STONE. AREAS CROSS HATCHED INDICATE SPECIFICATION LIMITS

TABLE 1.—*Gradings of coarse aggregates used in tests*

Coarse aggregate grading No.	Total per cent passing screens with round openings								
	3-inch	2½-inch	2-inch	1½-inch	1-inch	¾-inch	½-inch	¼-inch	⅛-inch
1	100	80	65	45	30		15	5	0
2	100	75	50	25	0				
3		100	85	70	50	40	25	5	0
4		100	75	55	35	25	15	5	0
5		100	65	35	0				
6			100	85	60	40	30	10	0
7			100	70	40	30	20	5	0
8			100	60	20	0			
9			100	40	30	25	20	5	0
10				100	80	60	40	10	0
11				100	60	40	15	5	0
12				100	40	10	0		
13					100	50	0		

The crushed stone was obtained from Bound Brook, N. J., and the gravel from Morrisville, Pa. The rock is representative of the extensive deposits of basalt (trap rock) quarried in northern New Jersey. This material is very hard and tough, showing a percentage of wear of 2.2 (French coefficient equals 18.2), apparent

specific gravity of 2.97 (weight per cubic foot, solid, 185 pounds), and a water absorption of 0.05 per cent. The gravel is representative of material of the type used extensively throughout this region. It consists essentially of rounded fragments of sandstone, flint, and quartz, has an apparent specific gravity of 2.65 (weight per cubic foot solid, of 165 pounds) and a water absorption of 0.68 per cent.

TABLE 2.—*Fineness moduli of aggregates used in tests*

Coarse aggregate grading No.	Maximum size	Fineness modulus	Sand required [1]
	Inches		*Per cent*
1	3	8.0	31
2	3	8.6	39
3	3	7.5	30
4	3	7.9	30
5	3	8.4	37
6	1½	7.2	35
7	2	7.5	30
8	2	8.0	37
9	2	7.6	32
10	1	6.8	39
11	1½	7.3	37
12	1½	7.7	42
13	1	7.2	45
Sand	----------	3.2	----------

[1] Calculated by fineness-modulus method for a designed strength of 3,500 pounds per square inch, slump of 1 inch and with the sand employed in these tests.

The fine aggregate used in the tests was also obtained at Morrisville, Pa., and meets all the conventional tests for first-grade concrete sand. The physical properties of the sand are shown below. Its apparent specific gravity was 2.65 (weight per cubic foot, solid, 165 pounds and its weight per cubic foot, dry, and shaken to refusal 108 pounds).

Physical properties of fine aggregate consisting essentially of subangular quartz grains containing some chert and sandstone

Sieve analysis:		
Total retained on ¼-inch screen	per cent	7
No. 10 sieve	do	24
No. 20 sieve	do	38
No. 30 sieve	do	62
No. 50 sieve	do	86
No. 100 sieve	do	95
Silt and clay	do	1.8
Weight per cubic foot (shaken to refusal)	pounds	108
Tensile strength ratio at 7 days	per cent	123
28 days	do	120

The cement was a standard Portland passing all physical test requirements. It was a brand used extensively in New Jersey.

TABLE 3.—*Weight per cubic foot and percentage of voids of coarse aggregates*

Coarse aggregate grading No.	Crushed stone		Gravel	
	Weight per cubic foot	Voids	Weight per cubic foot	Voids
	Pounds	*Per cent*	*Pounds*	*Per cent*
1	110	41	108	34
2	97	48	97	41
3	106	43	107	35
4	103	44	108	34
5	94	49	96	42
6	102	45	106	36
7	103	44	105	36
8	97	48	97	41
9	104	44	107	35
10	97	48	105	36
11	98	47	104	37
12	94	49	98	41
13	90	51	96	42

The percentage of voids for each aggregate in each of the 13 grading combinations as calculated from the apparent specific gravities and the unit weights are shown in Table 3. These values were used in all calculations of volume-weight relations.

TEST PROCEDURE FOR SERIES A

In series A the concrete was proportioned by volume, using a nominal mix of 1: 1¾: 3½. As far as could be measured by the use of the flow table, a constant consistency was maintained throughout the series, the quantity of water being varied as necessary. The flow test was made on the 30-inch flow table, using 30 drops from a height of one-half inch. In this report the flow is expressed as the final diameter in tenths of inches of a truncated cone of concrete, which had an original diameter at the base of 10 inches. For example, a flow of 140 indicates a final diameter of the base of 14 inches. The consistency employed, which was as nearly as possible that required in actual construction, gave a flow of 140 corresponding to a slump of from 1 inch to 2 inches. It was found necessary to vary the water-cement ratio from 0.67 to 0.83 in order to maintain a constant consistency throughout the range of coarse-aggregate gradings. The water-cement ratios used in series A are given in Table 4. No correction for water absorbed by the aggregate was made in calculating these values.

TABLE 4.—*Water-cement ratio used in series A to produce concrete of uniform consistency*

[Proportions: 1: 1¾: 3½ by volume. Consistency: Flow equals approximately 140]

Coarse aggregate grading No.	Water-cement ratio for stone concrete	Water-cement ratio for gravel concrete	Coarse aggregate grading No.	Water-cement ratio for stone concrete	Water-cement ratio for gravel concrete
1	0.76	0.76	8	0.71	0.74
2	.69	.70	9	.76	.74
3	.76	.77	10	.83	.78
4	.72	.70	11	.74	.74
5	.68	.66	12	.73	.70
6	.76	.75	13	.79	.74
7	.74	.72			

The actual quantities of materials required for each batch of concrete were determined by weight, using the volume-weight relations given in Table 3. A sufficient quantity of each size of aggregate was weighed for each batch, so as to secure the required total volume. In this way, all tendency toward segregation was avoided. In order to properly gauge the quantity of water required for each test batch, a trial batch of the same proportions was mixed by hand and the proper amount of water determined by trial. This procedure, while adding considerably to the labor involved, resulted in test batches of much greater uniformity in consistency than would otherwise have been possible.

The actual test batches were mixed in a 1-bag gasoline-driven mixer. For the gradings numbered 1 to 5, inclusive, the quantities of materials used in each batch were based on a coarse aggregate volume of 1.8 cubic feet, producing a slight excess of concrete over that required for one beam. For the gradings numbered 6 to 13, inclusive, quantities were based on a coarse-aggregate volume of 2.4 cubic feet, producing sufficient concrete for one beam and three cylinders. All batches were mixed for two minutes after all ingredients had been added. After mixing, the batch was dumped upon a water-tight platform, flow tests

for consistency made, and specimens cast. Concrete was rodded into molds in accordance with aproved methods of molding. Accurate determinations of yield were made by determining both the volume and the weight of the concrete remaining after the specimens had been cast.

Specimens were cured for 24 hours under damp cloths in the laboratory, after which the forms were removed and the specimens placed in a moist room until tested. Tests were made at 28 days and at 6 months.

To eliminate the effect of other variables on the relative strength of the crushed-stone and gravel concrete, specimens employing crushed stone and gravel of the same gradation were always cast in pairs. The entire series of gradations was also completed before being repeated, several days usually elapsing between the first and second rounds. Variations in temperature and humidity conditions throughout the test were compensated for in this way, making possible a more satisfactory comparison of the effect of aggregate grading on strength.

In testing the beams for flexural strength, two breaks were made on each specimen and the results averaged and reported, after calculation, as the modulus of rupture for the round. (See Table 5.) The corresponding values for round 2 were obtained in the same way. The average of the two rounds was reported as the average value for the type of aggregate, the grading, and the age involved. Each average value for modulus of rupture represents four breaks on two specimens tested on different days.

Average compression test values, as given in Table 6, were obtained in the same manner, except those for gradings Nos. 6 to 13, inclusive, each value for each round is the average of tests on three cylinders.

TABLE 5.—*Flexural strength of concrete specimens of series A mixed in the proportions 1 : 1¾ : 3½ by volume (nominal mix) and with a flow of approximately 140* [1]

Coarse aggregate grading No.	Modulus of rupture, 28-day tests						Modulus of rupture, 6-month tests					
	Stone			Gravel			Stone			Gravel		
	Round No. 1	Round No. 2	Average	Round No. 1	Round No. 2	Average	Round No. 1	Round No. 2	Average	Round No. 1	Round No. 2	Average
	Lbs. per sq. in.	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*
1	545	565	555	475	530	500	610	670	640	590	585	590
2	535	515	525	470	455	460	610	590	600	575	590	580
3	620	575	600	455	510	480	630	655	640	580	560	570
4	600	630	615	520	530	525	680	650	665	605	600	600
5	540	625	580	530	555	540	675	705	690	610	590	600
6	550	555	550	455	490	470	705	770	740	625	555	590
7	505	465	485	435	480	460	680	655	670	635	555	595
8	515	515	515	435	475	455	770	660	715	655	560	610
9	550	630	590	490	605	550	700	780	740	695	675	685
10	575	610	590	540	555	550	605	735	670	595	640	620
11	690	610	650	560	490	525	670	645	660	645	550	600
12	525	585	555	520	465	490	675	685	680	580	555	570
13	555	575	565	565	535	550	690	720	705	630	580	605
Average			570			505			680			600
Maximum			650			550			740			685
Minimum			485			455			600			570

[1] Determinations made on concrete beams 8 by 8 by 48 inches in size, tested as cantilevers. Each value is the average of two breaks on one beam.

TABLE 6.—*Compressive strength of concrete specimens of series A mixed in the proportions 1 : 1¾ : 3½ by volume (nominal mix) and with a flow of approximately 140* [1]

Coarse aggregate grading No.	Crushing strength, 28-day tests						Crushing strength, 6-month tests					
	Stone			Gravel			Stone			Gravel		
	Round No. 1	Round No. 2	Average	Round No. 1	Round No. 2	Average	Round No. 1	Round No. 2	Average	Round No. 1	Round No. 2	Average
	Lbs. per sq. in.	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*
1	4,255	3,160	3,710	3,580	3,020	3,300	None made.					
2	3,955	3,050	3,500	3,600	3,455	3,530						
3	4,300	3,385	3,840	3,595	3,565	3,580						
4	3,630	3,470	3,550	3,255	3,440	3,350						
5	3,510	3,760	3,635	3,475	3,370	3,420						
6	3,285	2,860	3,070	3,070	2,890	2,980	4,630	5,085	4,860	3,345	4,700	4,020
7	3,145	2,920	3,030	3,115	3,360	3,240	4,050	4,205	4,130	4,090	4,145	4,120
8	3,230	2,720	2,975	2,740	2,685	2,710	4,535	3,405	3,970	4,420	3,110	3,765
9	3,215	3,505	3,360	2,860	3,510	3,185	3,880	4,090	3,985	3,740	4,570	4,155
10	3,830	3,020	3,425	3,620	3,600	3,610	4,695	3,945	4,320	4,220	4,525	4,370
11	3,715	3,285	3,500	3,635	3,490	3,560	4,780	3,295	4,040	4,610	3,655	4,130
12	3,530	2,410	2,970	3,540	3,070	3,305	4,420	3,725	4,070	4,205	4,305	4,255
13	3,540	2,890	3,215	3,600	3,725	3,660	4,030	3,595	3,810	4,495	4,695	4,595
Average			3,370			3,340			4,150			4,180
Maximum			3,840			3,660			4,860			4,595
Minimum			2,970			2,710			3,810			3,765

[1] For coarse aggregate gradings Nos. 1 to 5, inclusive, crushing-strength tests were made on portions of beams from flexure tests; each value is the average of two tests For coarse aggregate gradings Nos. 6 to 13, inclusive, crushing-strength tests were made on 6 by 12 inch cylinders; each value is the average of three tests.

TEST PROCEDURE FOR SERIES B

In series B an entirely different method of proportioning was employed, but the various details of mixing, molding, curing, and testing were exactly the same as in series A. In this series the concrete was designed according to the so-called trial method application of the water-cement ratio theory which is being advocated by the Portland Cement Association and which is described in a bulletin[1] published by the association. The design called for a crushing strength at 28 days of 3,500 pounds, using a water-cement ratio of 0.72. The object was to secure data showing how variations in the type and gradation of coarse aggregate and the ratio of fine to coarse aggregate would affect the strength and yield when proportioned by the trial method.

To secure a uniform consistency as used in series A but with a constant water-cement ratio, the procedure in determining the proper proportions was as follows:

A paste of water and cement in the ratio required (0.72) was prepared and added to a mixture of fine and coarse aggregate until a consistency was obtained approximating a flow of 140. Three mixtures of fine and coarse aggregate were used. They were proportioned by volume in the following ratios, 33:67, 36:64, and 40:60. Trials were made with small hand-mixed batches for each type and grading of coarse aggregate, using each of the ratios of fine to coarse aggregate, and the proportions for the test batches were calculated from the resulting weights. The calculated proportions in series B for all combinations are given in Table 7. This work was done in strict accordance with the procedure recommended by the Portland Cement Association for the design of concrete mixtures.

There were slight differences in consistency between the machine-mixed batches and the small trial batches, even when gauged with the same amount of water, and some preliminary experimental work was necessary to establish the relation between the two. After a little experience it was found possible to proportion the trial batches for a water-cement ratio of 0.72, so that the consistency of the large test batches after two minutes mixing would not vary more than ±5 points from a flow of 140. Any batches showing a greater deviation were discarded.

The necessity of maintaining a uniform consistency was recognized. It is realized, of course, that there is an intimate relation between consistency, water-cement ratio, and proportions for different gradations of aggregate. If any two of these factors are kept constant, it is necessary to vary the other whenever the aggregate grading varies. In this case only the coarse aggregate varied and the sand remained constant. In series A the proportions and consistency were kept constant and the water-cement ratio varied, while in series B the consistency and water-cement ratio were kept constant and the proportions varied. The latter is, of course, the rational method if we assume that strength is proportional to water-cement ratio within the range of workable mixtures.

STRENGTH DATA OBTAINED IN SERIES A DISCUSSED

As previously stated, the tests included in series A were made to obtain some definite information as to the relative strength and yield of crushed-stone and gravel concrete when proportioned in accordance with current New Jersey specifications and with the various coarse-aggregate gradings indicated.

The results of the flexure tests at both 28 days and 6 months are given in Table 5 and are plotted in Figure 3. An examination of this table indicates that the crushed-stone concrete is considerably higher in flexural strength than the gravel concrete. The average increase for all 13 gradations is seen to be 65 pounds per square inch at 28 days, and 80 pounds per square inch at 6 months; approximately 13 per cent in both cases. The concordance of the results is quite remarkable in view of the rather limited number of test specimens involved. Out of a total of 52 pairs of test specimens in the group, the crushed-stone concrete shows higher flexural strength in 49 cases; the values are the same in one case and the gravel concrete shows higher values in two cases. An inspection of the averages of the two rounds shows the crushed-stone concrete higher in all cases, as is indicated graphically in Figure 3. The results given in Table 6 and plotted in Figure 4, however, indicate that this difference is not reflected in the crushing strength of the concrete, the crushed-stone concrete in this case averaging practically the same as the gravel concrete at each period. These tables and figures do not reveal any consistent relation between either maximum size or gradation

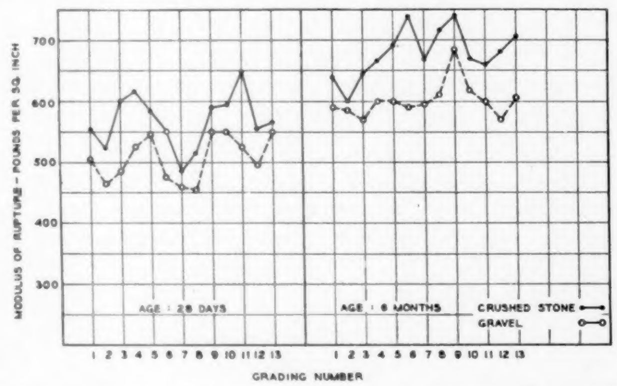


FIG. 3.—RESULTS OF FLEXURE TESTS OF CONCRETE SPECIMENS OF SERIES A

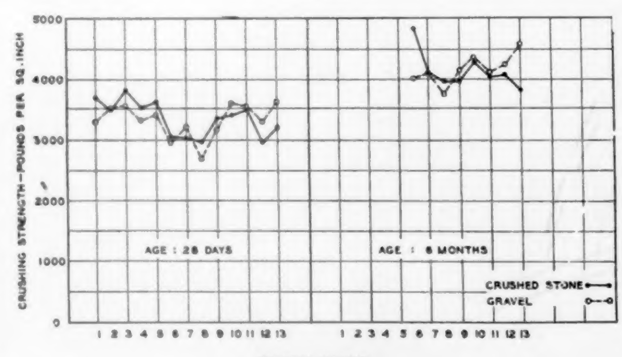


FIG. 4.—RESULTS OF CRUSHING STRENGTH TESTS OF CONCRETE SPECIMENS OF SERIES A

of coarse aggregate and the strength, either flexural or crushing. This is not particularly surprising in view of the small number of specimens of each gradation represented. This would seem to indicate that possibly variations in grading do not have a very marked effect upon strength, at least in so far as concrete of

[1] DESIGN AND CONTROL OF CONCRETE MIXTURES, published by the Portland Cement Association, Chicago, Ill.

this particular proportion (1 : 1¾ : 3½) is concerned. It is true that a number of the mixes were undersanded when judged by the standard set-up by the fineness-modulus method of proportioning. Gradings Nos. 2, 5, 8, 10, 11, 12, and 13 when proportioned by this method would require a sand-coarse aggregate ratio of approximately 2 : 3 instead of 1 : 2 as given by the 1 : 1¾ : 3½ mix.

In the case of the smaller aggregates, as for instance gradings Nos. 10 to 13, inclusive, it is probable that this additional sand would have necessitated sufficient additional water for the same consistency to cause an appreciable lowering of the strength. Variations in the water-cement ratio required because of variations in coarse-aggregate grading with a fixed quantity of sand, as used in this series (Table 4) do not appear to be sufficient to affect the strength consistently. This fact is of considerable practical significance because it indicates that changes in the water content made necessary on the job to maintain a given consistency when variations in coarse-aggregate grading occur do not affect the strength as much as is sometimes supposed. There is, however, a very appreciable effect on yield, and therefore on relative economy, which will be discussed later.

STRENGTH DATA OBTAINED IN SERIES B DISCUSSED

The data secured as the result of tests of series B are interesting because we have not only an opportunity to study variation in strength for a fixed water-cement ratio, but we can also study the effect of variation in the ratio of sand to coarse aggregate on the strength and yield. It will be remembered that in this series the concrete was proportioned by trial so as to give a consistency of 140 by the flow test for a water-cement ratio of 0.72 and that three sand-coarse-aggregate ratios were employed, 33 : 67, 36 : 64, and 40 : 60. The actual proportions which were derived are given in Table 7, and vary all the way from a 1 : 1.67 : 2.50 mix for grading No. 10, stone (40 : 60 ratio), to a 1 : 1.98 : 3.96 mix for grading No. 2, gravel (33 : 67 ratio). The resulting yield and therefore economy of these mixes will be discussed later. These mixes were all designed to give a crushing strength at 28 days of 3,500 pounds per square inch.

TABLE 7.—*Proportions used in series B to obtain flow of 140 with water-cement ratio of 0.72*

Coarse aggregate grading No.	Ratio sand to coarse aggregate 33: 67		Ratio sand to coarse aggregate 36: 64		Ratio sand to coarse aggregate 40: 60	
	Stone	Gravel	Stone	Gravel	Stone	Gravel
1	1: 1. 68: 3. 37	1: 1. 72: 3. 44	1: 1. 72: 3. 06	1: 1. 81: 3. 22	1: 1. 78: 2. 67	1: 1. 85: 2. 78
2	1: 1. 96: 3. 92	1: 1. 98: 3. 96	1: 1. 96: 3. 49	1: 2. 01: 3. 58	1: 2. 05: 3. 07	1: 2. 14: 3. 21
3	1: 1. 62: 3. 24	1: 1. 68: 3. 36	1: 1. 70: 3. 03	1: 1. 82: 3. 24	1: 1. 86: 2. 79	1: 1. 92: 2. 88
4	1: 1. 79: 3. 58	1: 1. 63: 3. 27	1: 1. 84: 3. 28	1: 1. 85: 3. 29	1: 1. 93: 2. 90	1: 1. 99: 2. 99
5	1: 1. 88: 3. 75	1: 1. 90: 3. 80	1: 1. 97: 3. 51	1: 1. 99: 3. 55	1: 1. 92: 2. 88	1: 2. 18: 3. 28
6	1: 1. 52: 3. 04	1: 1. 55: 3. 11	1: 1. 63: 2. 90	1: 1. 66: 2. 95	1: 1. 84: 2. 76	1: 1. 88: 2. 82
7	1: 1. 57: 3. 14	1: 1. 70: 3. 39	1: 1. 80: 3. 20	1: 1. 73: 3. 08	1: 1. 82: 2. 73	1: 1. 88: 2. 82
8	1: 1. 84: 3. 68	1: 1. 87: 3. 75	1: 1. 93: 3. 44	1: 1. 95: 3. 47	1: 2. 02: 3. 03	1: 2. 01: 3. 02
9	1: 1. 67: 3. 34	1: 1. 71: 3. 42	1: 1. 90: 3. 38	1: 1. 81: 3. 22	1: 1. 78: 2. 68	1: 1. 89: 2. 83
10	1: 1. 47: 2. 94	1: 1. 47: 2. 94	1: 1. 53: 2. 72	1: 1. 52: 2. 71	1: 1. 67: 2. 50	1: 1. 78: 2. 68
11	1: 1. 59: 3. 18	1: 1. 62: 3. 24	1: 1. 70: 3. 03	1: 1. 72: 3. 06	1: 1. 91: 2. 87	1: 1. 83: 2. 74
12	1: 1. 72: 3. 44	1: 1. 82: 3. 64	1: 1. 90: 3. 38	1: 1. 80: 3. 20	1: 2. 06: 3. 09	1: 2. 03: 3. 05
13	1: 1. 62: 3. 24	1: 1. 67: 3. 35	1: 1. 74: 3. 10	1: 1. 71: 3. 05	1: 1. 91: 2. 86	1: 1. 93: 2. 90

The results of the flexural strength test for each of the three aggregate ratios are shown in Table 8 and are plotted in Figure 5. Inspecting general averages, not only were almost identical values for moduli of rupture at 28 days found as were found for series A, but what is somewhat more significant, the same relative increase in strength for the crushed-stone concrete as compared with the gravel concrete was found. These average values are grouped together for comparison in Table 9 and Figure 6. The percentage of increase, is however, not quite so great, ranging from 10 per cent for the 33:67 mix to 13 per cent for the 40:60 combination.

The figures demonstrate the danger of designing concrete for resistance to flexure solely on the basis of water-cement ratio without regard to the type of aggregate employed.

Reverting again to Figure 5 and discussing the detail values for flexural strength in series B, it is seen that the graphs show considerable variation in strength. Attention should be called, however, to the fact that the vertical scale to which these values have been plotted is very large and that in reality the deviations from the group averages are in general quite small.

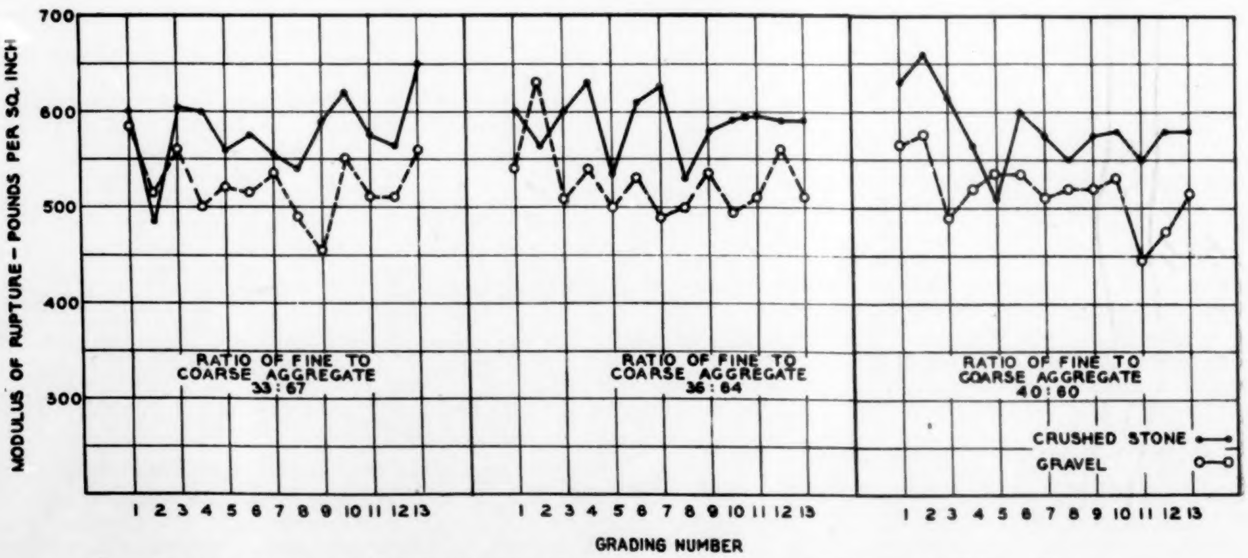


FIG. 5.—RESULTS OF FLEXURE TESTS OF CONCRETE SPECIMENS OF SERIES B, 28-DAY TESTS

TABLE 8.—*Flexural strength of concrete specimens of series B, 28-day tests* [1]

Coarse aggregate grading No.	Ratio sand to coarse aggregate 33:67						Ratio sand to coarse aggregate 36:64						Ratio sand to coarse aggregate 40:60					
	Stone			Gravel			Stone			Gravel			Stone			Gravel		
	Round No. 1	Round No. 2	Average	Round No. 1	Round No. 2	Average	Round No. 1	Round No. 2	Average	Round No. 1	Round No. 2	Average	Round No. 1	Round No. 2	Average	Round No. 1	Round No. 2	Average
	Lbs. per sq. in.	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*
1	660	540	600	640	530	585	615	585	600	525	555	540	690	565	630	575	550	560
2	520	450	485	515	515	515	565	560	560	570	685	630	720	595	660	625	520	570
3	570	640	605	575	540	560	560	635	600	510	505	510	585	645	615	475	505	490
4	580	620	600	505	500	500	605	655	630	525	550	540	555	570	560	525	510	520
5	590	525	560	505	530	520	560	505	530	480	525	500	495	525	510	545	520	530
6	590	555	570	530	500	515	580	640	610	500	560	530	600	605	600	530	535	530
7	565	545	555	555	510	530	665	590	630	515	465	490	565	585	575	470	550	510
8	525	550	540	490	485	490	585	475	530	525	480	500	550	545	550	490	545	520
9	575	605	590	510	400	455	600	555	580	540	525	530	575	575	575	545	490	520
10	600	645	620	505	590	550	600	580	590	510	475	490	580	575	580	540	520	530
11	595	555	575	515	500	510	600	590	595	480	535	510	575	530	550	420	465	440
12	560	570	565	515	500	510	575	600*	590	545	570	560	620	535	580	490	455	470
13	665	630	650	530	585	560	595	585	590	510	510	510	595	565	580	495	535	515
Average			580			525			590			525			580			515
Maximum			650			585			630			630			660			570
Minimum			485			455			530			490			510			440

[1] Determinations made on concrete beams 8 by 8 by 48 inches in size. Each value is the average of two breaks on one beam.

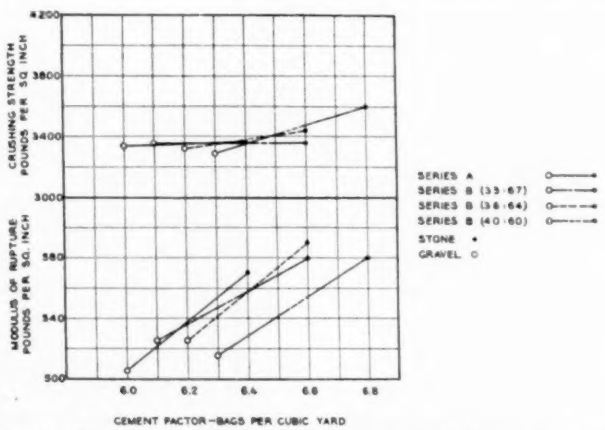


FIG. 6.—RELATION BETWEEN STRENGTH OF CONCRETE AND CEMENT FACTOR. GENERAL AVERAGES FOR ALL GRADINGS

TABLE 9.—*Comparison of average results of 28-day tests of series A and series B*

Series	Coarse aggregate	Ratio of fine to coarse aggregate	Average modulus of rupture	Average crushing strength	Average cement factor
			Lbs. per sq. in.	*Lbs. per sq. in.*	*Bags per cu. yd.*
A	Stone	33:67	570	3,370	6.4
	Gravel	33:67	505	3,340	6.0
B	Stone	33:67	580	3,360	6.6
	Gravel	33:67	525	3,360	6.1
B	Stone	36:64	590	3,440	6.6
	Gravel	36:64	525	3,310	6.2
B	Stone	40:60	580	3,600	6.8
	Gravel	40:60	515	3,290	6.3

NOTE.—Each value for flexural strength is the average of 52 tests.
Each value for crushing strength is the average of 68 tests.
In series A the proportions were 1:1¾:3½ by volume; flow, 140; water-cement ratio varied from 0.67 to 0.81.
In series B the proportions were determined by trial (Portland Cement Association method to give a flow of 140, with a water-cement ratio of 0.72).

Table 10 shows the deviations in percentage of the individual values for each grading and type of aggregate from the group average. It will be seen that the average deviations for the three groups in series B are essentially the same and are slightly less than those in series A. It is interesting to note also that in six cases out of eight, grading No. 2 shows a deviation in excess of 5 per cent. This was a poorly graded material with a maximum size of 3 inches. The most significant detail as regards these figures, however, is the fact that for all intents and purposes the flexural strengths obtained in series B for each type of aggregate are practically uniform, the deviation being no more than must be expected even in carefully conducted laboratory work.

TABLE 10.—*Deviations in per cent of individual values for flexural strength from the mean of each group and for each material, based on 28-day tests* [1]

Coarse aggregate grading No.	Series A		Series B					
	Stone	Gravel	Ratio fine to coarse aggregate, 33:67		Ratio fine to coarse aggregate 36:64		Ratio fine to coarse aggregate 40:60	
			Stone	Gravel	Stone	Gravel	Stone	Gravel
	Per ct.	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*
1	−3	−1	+3	+11	+2	+3	+9	+9
2	−8	−9	−16	−2	−5	+20	+14	+11
3	+5	−5	+4	+7	+2	−3	+6	−5
4	+8	+4	+3	−5	+7	+3	−3	+1
5	+2	+7	−3	−1	−10	−5	−12	+3
6	−4	−7	−2	−2	+3	+1	+3	+3
7	−15	−9	−4	+1	+7	−7	−1	−1
8	−10	−10	−7	−7	−10	−5	−5	+1
9	+4	+9	+2	−13	−2	+1	−1	+1
10	+4	+9	+7	+5	0	−7	0	+3
11	+14	+4	−1	−3	+1	−3	−5	−15
12	−3	−3	−3	−3	0	+7	0	−3
13	−1	+9	+12	+7	0	−3	0	0
Average deviation	6	7	5	5	4	5	5	5

[1] Total number of values, 104. Number in which deviation exceeds 10 per cent, 11; number in which deviation exceeds 5 per cent, 38; number in which deviation is 5 per cent or less, 66.

The results of crushing strength tests on specimens of series B are shown in Table 11 and are plotted in Figure 7. The group averages are summarized in Table 9. As in the case of the flexure tests, the deviation from the averages are, in general, neither consistent nor of great magnitude. Either of the three aggregate ratios seem to produce concrete of about the same strength regardless of grading, which again seems to indicate that so far as strength alone is concerned grading of coarse aggregate within the limits here indicated is not an important factor. The words "strength alone" are used here and elsewhere advisedly.

Aside from the yield or relative economy of the different gradations, which is a subject entirely apart from the question of quality, variations in grading which produce harsh concrete difficult to handle and place, will unquestionably affect the strength on the job, because of the invariable tendency of the concrete gang to use excess water with such a mix. In these tests an effort was made to secure comparable workability of the different batches by means of the flow test. The slump test was, of course, entirely unsuited to this kind of work. The flow test was used because there was nothing better. It is, however, not a test for workability in the strict sense of the word, so that several of the undersanded mixtures with the ratio of fine to coarse aggregate of 33 : 67 were probably unworkable in the sense that they would have been difficult to place and finish on the job. The point that it is intended to emphasize is, that it was possible to control the water-cement ratio in the laboratory but it would not be at all easy in actual construction unless the control was very rigid.

Table 11.—*Results of crushing strength tests of specimens of series B at age of 28 days* [1]

RATIO OF FINE TO COARSE AGGREGATE 33 : 67

Coarse aggregate grading No.	Crushed stone			Gravel		
	Round No. 1	Round No. 2	Average	Round No. 1	Round No. 2	Average
	Lbs. per sq. in.	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*
1	3, 370	3, 215	3, 290	3, 230	3, 595	3, 410
2	3, 370	3, 040	3, 205	3, 220	3, 185	3, 200
3	4, 230	3, 860	4, 045	3, 785	3, 855	3, 820
4	3, 825	4, 065	3, 945	3, 690	3, 240	3, 465
5	3, 590	3, 150	3, 370	3, 820	2, 605	3, 210
6	3, 710	3, 205	3, 460	3, 345	4, 075	3, 710
7	3, 455	3, 145	3, 300	3, 375	3, 410	3, 390
8	2, 950	2, 645	2, 800	3, 200	3, 210	3, 205
9	3, 695	2, 985	3, 340	3, 365	3, 720	3, 540
10	4, 025	3, 090	3, 560	3, 490	3, 405	3, 450
11	3, 710	3, 000	3, 355	3, 635	2, 580	3, 210
12	3, 025	2, 580	2, 800	3, 120	2, 535	2, 830
13	3, 465	2, 945	3, 205	3, 205	3, 315	3, 260
Average			3, 360			3, 360
Maximum			4, 045			3, 820
Minimum			2, 800			2, 830

RATIO OF FINE TO COARSE AGGREGATE 36 : 64

Coarse aggregate grading No.	Crushed stone Round No. 1	Crushed stone Round No. 2	Crushed stone Average	Gravel Round No. 1	Gravel Round No. 2	Gravel Average
1	3, 520	3, 245	3, 380	3, 605	3, 385	3, 495
2	3, 090	3, 075	3, 080	3, 245	4, 015	3, 630
3	3, 975	3, 560	3, 770	3, 165	3, 160	3, 160
4	3, 645	4, 060	3, 850	3, 190	3, 325	3, 260
5	3, 455	3, 375	3, 415	2, 975	3, 685	3, 330
6	3, 790	3, 805	3, 800	3, 190	3, 815	3, 500
7	3, 285	3, 925	3, 605	3, 085	3, 215	3, 150
8	2, 845	2, 895	2, 870	2, 885	2, 725	2, 805
9	3, 125	3, 190	3, 160	3, 170	3, 000	3, 085
10	3, 550	3, 950	3, 750	3, 640	3, 680	3, 660
11	3, 175	3, 785	3, 480	3, 225	3, 935	3, 580
12	3, 025	3, 310	3, 170	3, 440	2, 990	3, 215
13	3, 225	3, 580	3, 400	2, 870	3, 515	3, 190
Average			3, 440			3, 310
Maximum			3, 850			3, 660
Minimum			2, 870			2, 805

RATIO OF FINE TO COARSE AGGREGATE 40 : 60

Coarse aggregate grading No.	Crushed stone Round No. 1	Crushed stone Round No. 2	Crushed stone Average	Gravel Round No. 1	Gravel Round No. 2	Gravel Average
1	3, 970	3, 360	3, 665	3, 040	3, 460	3, 250
2	3, 335	3, 805	3, 570	3, 490	3, 425	3, 460
3	3, 765	4, 065	3, 915	3, 045	3, 890	3, 470
4	3, 670	4, 190	3, 930	3, 240	2, 895	3, 070
5	3, 500	3, 590	3, 545	3, 365	3, 150	3, 260
6	4, 165	3, 385	3, 775	3, 490	3, 460	3, 475
7	3, 540	2, 865	3, 200	3, 180	3, 630	3, 405
8	3, 200	3, 060	3, 130	3, 285	3, 115	3, 200
9	3, 720	3, 475	3, 600	3, 190	2, 970	3, 080
10	4, 055	3, 920	3, 990	3, 610	3, 260	3, 435
11	3, 610	3, 600	3, 605	3, 480	3, 285	3, 380
12	3, 145	3, 235	3, 190	3, 020	2, 625	2, 820
13	3, 435	3, 905	3, 670	3, 540	3, 365	3, 450
Average			3, 600			3, 290
Maximum			3, 990			3, 475
Minimum			3, 130			2, 820

[1] For coarse-aggregate gradings 1 to 5, inclusive, crushing-strength tests were made on portion of beams from flexure tests. Each value is the average of two breaks. For coarse-aggregate gradings 6 to 13, inclusive, crushing-strength tests were made on 6 by 12 inch cylinders. Each value is average of three tests.

ABSORPTION TESTS MADE

A short series of absorption tests was made on the concrete of series A at age of six months. The results are given in Table 12 and indicate that there is practically no difference between the absorption of the stone and the gravel concrete. These tests were made by immersing samples of concrete from the broken beams in water for 24 hours and noting the increase in weight.

Table 12.—*Absorption tests on concrete of series A at age of six months*

Coarse aggregate grading No.	Water absorbed by stone concrete			Water absorbed by gravel concrete		
	Specimen No. 1	Specimen No. 2	Average	Specimen No. 1	Specimen No. 2	Average
	Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
1	5. 5	5. 0	5. 3	4. 8	5. 9	5. 4
2	5. 8	4. 8	5. 3	4. 8	5. 2	5. 0
3	5. 9	5. 6	5. 8	5. 6	5. 5	5. 6
4	4. 3	5. 1	4. 7	4. 5	5. 0	4. 8
5	4. 3	5. 6	5. 0	4. 9	5. 0	5. 0
6	5. 6	5. 6	5. 6	5. 6	5. 8	5. 7
7	5. 6	5. 6	5. 6	5. 1	4. 9	5. 0
8	5. 0	6. 3	5. 7	5. 0	5. 4	5. 2
9	6. 0	5. 8	5. 9	4. 8	5. 2	5. 0
10	6. 2	5. 8	6. 0	5. 1	6. 0	5. 6
11	5. 2	5. 7	5. 5	4. 8	5. 9	5. 4
12	4. 9	5. 0	5. 0	5. 2	5. 8	5. 5
13	5. 4	5. 8	5. 6	5. 6	5. 5	5. 6
Average			5. 5			5. 3

YIELD OF CONCRETE DISCUSSED

A study of the relative economy of various concrete mixtures, all of which may have the same strength, is just beginning to occupy the attention of engineers and progressive contractors. It was formerly assumed and is still stated in many handbooks that, for a given proportion of cement, sand, and coarse aggregate, definite amounts of materials are required to produce a cubic yard of concrete. While the values given may be correct as average values it is known that there are many factors which may appreciably alter any one or more of these quantities under certain conditions. In this report the writer is concerned primarily with the effect of type and gradation of coarse aggregate on yield.

SERIES A

Table 13 gives the computed quantities of material required for 1 cubic yard of concrete for each type and gradation of aggregate used in these tests, while Table 14 gives the corresponding solid volumes of the materials and the density of the concrete (total solids expressed as a percentage of 27 cubic feet). Quantities of materials are plotted in Figures 8 and 9. These figures illustrate graphically the fluctuations in the quantities of materials required to produce 1 cubic yard of concrete due to variations in the grading of the coarse aggregate. Assuming unit costs for cement, sand, and coarse aggregate, these values may be used to determine the cost of the materials in a cubic yard of concrete for each grading and aggregate type shown. Allowance should be made for the fact that the figures for any particular case may be somewhat out of line because of inaccuracies which result from experimental

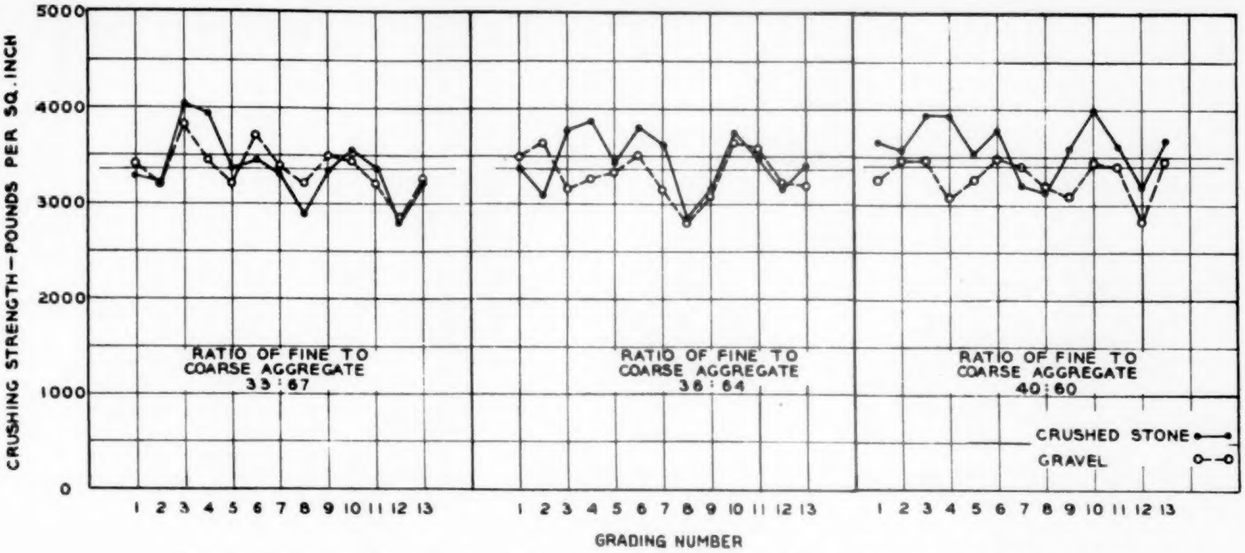


FIG. 7.—CRUSHING STRENGTH OF CONCRETE SPECIMENS OF SERIES B AT AGE OF 28 DAYS

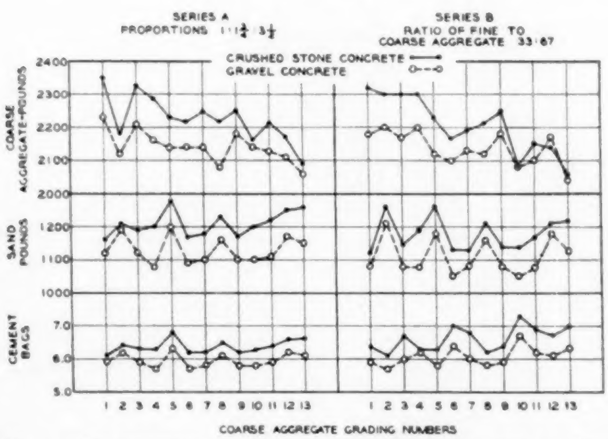


FIG. 8.—QUANTITIES OF MATERIALS REQUIRED FOR 1 CUBIC YARD OF CONCRETE

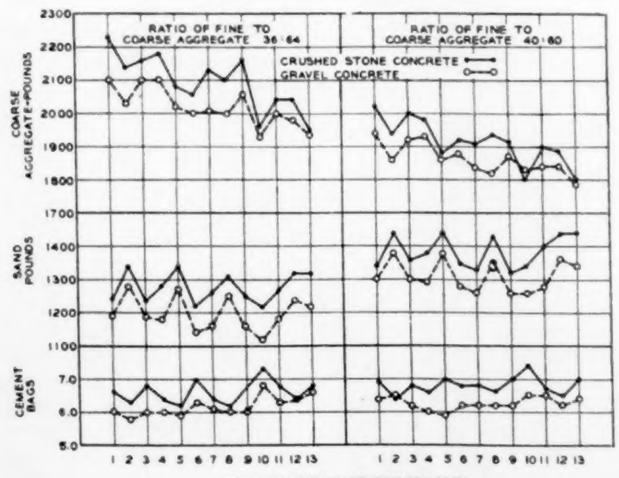


FIG. 9.—QUANTITIES OF MATERIALS REQUIRED FOR 1 CUBIC YARD OF CONCRETE

TABLE 13.—*Quantities of material required for 1 cubic yard of concrete, using the proportions 1 : 1¾ : 3½ by volume (nominal mix, series A)*

Coarse aggregate grading No.	Stone			Gravel		
	Cement	Sand	Stone	Cement	Sand	Gravel
	Bags	*Pounds*	*Pounds*	*Bags*	*Pounds*	*Pounds*
1	6.1	1,160	2,350	5.9	1,120	2,230
2	6.4	1,210	2,180	6.2	1,190	2,120
3	6.3	1,190	2,330	5.9	1,120	2,210
4	6.3	1,200	2,290	5.7	1,080	2,160
5	6.8	1,280	2,230	6.3	1,200	2,140
6	6.2	1,170	2,220	5.7	1,090	2,140
7	6.2	1,180	2,250	5.8	1,100	2,140
8	6.5	1,230	2,220	6.1	1,160	2,080
9	6.2	1,170	2,250	5.8	1,100	2,180
10	6.3	1,200	2,160	5.8	1,100	2,140
11	6.4	1,220	2,210	5.9	1,110	2,130
12	6.6	1,250	2,170	6.2	1,170	2,110
13	6.6	1,260	2,090	6.1	1,150	2,060
Average	6.4	1,210	2,230	6.0	1,130	2,140

TABLE 14.—*Solid volumes of material for 1 cubic yard of concrete for each mix of series A and total solids or density of concrete expressed as a percentage of maximum possible density*

Coarse aggregate grading No.	Stone				Gravel			
	Solid volumes			Total solids	Solid volumes			Total solids
	Cement	Sand	Stone		Cement	Sand	Gravel	
	Cu. ft.	*Cu. ft.*	*Cu. ft.*	*Per cent*	*Cu. ft.*	*Cu. ft.*	*Cu. ft.*	*Per cent*
1	2.96	7.04	12.70	84	2.86	6.79	13.52	86
2	3.11	7.33	11.78	81	3.01	7.21	12.84	85
3	3.06	7.22	12.60	85	2.86	6.79	13.40	85
4	3.06	7.27	12.38	84	2.77	6.54	13.10	83
5	3.30	7.76	12.05	86	3.06	7.27	12.98	86
6	3.01	7.09	12.00	82	2.77	6.61	12.98	83
7	3.01	7.15	12.17	83	2.82	6.67	12.98	83
8	3.16	7.45	12.00	84	2.96	7.03	12.60	84
9	3.01	7.09	12.17	83	2.82	6.67	13.21	84
10	3.06	7.27	11.68	81	2.82	6.67	12.98	83
11	3.11	7.39	11.94	83	2.86	6.73	12.91	83
12	3.21	7.58	11.72	83	3.01	7.09	12.79	85
13	3.21	7.64	11.30	82	2.96	6.97	12.49	83

errors. For this reason, comparisons of the effect of aggregate type on yield should only be made on averages for all gradations, as in this way the number of specimens tend to largely eliminate the effect of experimental errors. The results for the individual gradings, however, are of interest to the extent that they indicate general relationships. For example, Figures 8 and 9 show at a glance the effect of gradings 2, 5, 8, 12, and 13 on the various quantities required to produce a cubic yard of concrete. The amount of cement and sand required is larger and the amount of coarse aggregate required is smaller than where the coarse aggregate contains the smaller sizes.

To bring out certain possible cost relations and illustrate the economic features involved in this study in a more graphic way than could be done by a comparison of quantities only, certain unit costs of materials have been assumed. These costs are said to apply fairly well to conditions in New Jersey and are as follows: Cement, 60 cents per bag; sand, 50 cents per ton; and coarse aggregate $1.40 per ton. The resulting material costs per cubic yard are shown in Figures 10 and 11. Note the relative high cost resulting from the use of gradings 2, 5, 8, and 12 of series A. The value for grading No. 2 crushed stone is evidently in error as this point should be considerably higher than shown. On the basis of the above unit prices, the average cost of materials for 1 cubic yard of gravel concrete 1:1¾:3½ mix by volume is $5.38, while the corresponding value for the crushed stone concrete is $5.70, an increase of 32 cents, or approximately 6 per cent. These values and those for series B, together with the corresponding moduli of rupture are given in Table 17. Values may be calculated in a similar way for any combination of unit prices.

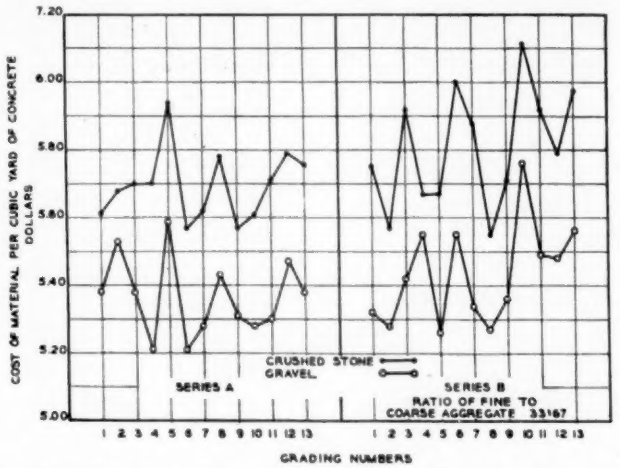


FIG. 10.—RELATION BETWEEN GRADING OF COARSE AGGREGATE AND TOTAL COST OF MATERIAL TO PRODUCE 1 CUBIC YARD OF CONCRETE

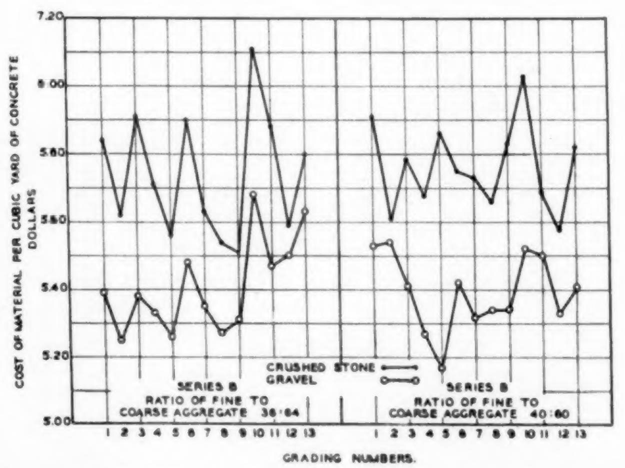


FIG. 11.—RELATION BETWEEN GRADING OF COARSE AGGREGATE AND TOTAL COST OF MATERIAL TO PRODUCE 1 CUBIC YARD OF CONCRETE

YIELD OF SERIES B

Data for quantities of material used and densities of concrete as determined for series B are shown in Tables 15 and 16. The quantities and corresponding costs are plotted in Figures, 8, 9, 10, and 11 and Table 17. These data show approximately the same relative difference in cost between the gravel and the stone concrete as in series A. It is interesting to note, however, that one factor which produces high costs in concrete proportioned as in series A, has just the opposite effect when proportioning is by the water-cement ratio trial method. When a contractor is working under a straight water-cement ratio specification, and sand is cheaper than coarse aggregate, as in this case, it is to his advantage to use a poorly graded stone or gravel because in so doing he is able to crowd more aggregate into his cement paste before passing the bounds of workability. On the other hand, the high cost of using a grading such as No. 10 with a large proportion of relatively small sizes is at once apparent, especially with the smaller proportions of sand.

SLABS OF EQUIVALENT STRENGTH DETERMINED

It is of interest to compute the relative theoretical thicknesses of slab required to produce pavements of equivalent transverse strength, using the average values of modulus of rupture for the two classes of concrete as shown by the tests of series A. For this purpose the so-called corner formula,[2] which is used extensively in the calculation of edge thickness for concrete pavement slabs, is employed. This formula is usually expressed as follows:

$$d=\sqrt{\frac{3P}{s}}$$

in which d=depth of slab in inches;
s=allowable unit flexural stress in bending in the concrete;
and P=allowed wheel-load at corner in pounds.

In both cases the usual maximum allowable unit stress of one-half the modulus of rupture will be employed in the calculation. In the case of the gravel concrete this gives an allowable stress of 253 pounds per square inch and for the stone concrete a corresponding value of 285 pounds per square inch. Assuming a load at the corner of 8,000 pounds in each case, the value of d for the crushed-stone concrete reduces to 9.18 inches and for the gravel concrete to 9.74 inches, an increase of 0.56 inch, or 6.1 per cent. For equivalent slab strengths and on the basis of the flexural-strength values in the concrete obtained from these tests, pavements constructed of gravel concrete should be approximately one-half inch thicker than pavements constructed of crushed-stone concrete.

[2] OLDER, CLIFFORD. HIGHWAY RESEARCH IN ILLINOIS. Proc. A. S. C. E., 1924, p. 1180.

Reverting again to the previously assumed unit costs and adding 6.1 per cent to the cost of 1 cubic yard of gravel concrete as shown at $5.38, a value of $5.71 is obtained, which is almost exactly equal to the unit cost per cubic yard of the stone concrete. In other words, for the unit prices assumed, the cost of materials required to produce concrete pavements of the same slab strength is almost exactly the same for both aggregates. A similar cost analysis may, of course, be made with any other combination of unit prices. For example, assuming cement at 50 cents per bag, sand and gravel at $1.20 per ton, and crushed stone at $1.40 per ton, the unit cost of a cubic yard of gravel concrete (series A) is found to be $4.96, with $5.49 as the corresponding cost for the stone concrete, an increase of 53 cents. In this case, adding 6½ per cent to the cost of the gravel concrete to care for the added thickness, makes the total cost of material in a gravel concrete slab of equivalent strength $5.26 as against $5.49 for the stone concrete.

TABLE 15.—*Quantities of materials required for 1 cubic yard of concrete, series B*

Coarse aggregate grading No.	Stone			Gravel		
	Cement	Sand	Stone	Cement	Sand	Gravel
RATIO OF FINE TO COARSE AGGREGATE 33 : 67						
	Bags	*Pounds*	*Pounds*	*Bags*	*Pounds*	*Pounds*
1	6.4	1,120	2,320	5.9	1,080	2,180
2	6.1	1,260	2,300	5.7	1,210	2,200
3	6.7	1,150	2,300	6.0	1,080	2,170
4	6.3	1,190	2,300	6.2	1,080	2,200
5	6.3	1,260	2,230	5.8	1,170	2,120
6	7.0	1,130	2,170	6.4	1,050	2,100
7	6.8	1,130	2,190	6.0	1,080	2,130
8	6.2	1,210	2,210	5.8	1,160	2,120
9	6.4	1,140	2,250	5.9	1,080	2,180
10	7.3	1,140	2,080	6.7	1,050	2,080
11	6.9	1,170	2,150	6.2	1,080	2,100
12	6.7	1,210	2,140	6.1	1,180	2,170
13	7.0	1,220	2,060	6.3	1,130	2,040
Average	6.6	1,180	2,210	6.1	1,110	2,140
RATIO OF FINE TO COARSE AGGREGATE 36 : 64						
1	6.6	1,240	2,230	6.0	1,190	2,100
2	6.3	1,340	2,140	5.8	1,280	2,030
3	6.8	1,240	2,160	6.0	1,190	2,100
4	6.4	1,280	2,180	6.0	1,180	2,100
5	6.2	1,340	2,080	5.9	1,270	2,020
6	7.0	1,220	2,060	6.3	1,140	2,000
7	6.4	1,260	2,130	6.1	1,160	2,010
8	6.2	1,310	2,100	6.0	1,250	2,000
9	6.1	1,250	2,160	6.0	1,160	2,060
10	7.4	1,220	1,960	6.8	1,120	1,930
11	6.8	1,270	2,040	6.3	1,180	2,000
12	6.4	1,320	2,040	6.4	1,240	1,980
13	6.8	1,320	1,950	6.6	1,220	1,940
Average	6.6	1,280	2,100	6.2	1,200	2,020
RATIO OF FINE TO COARSE AGGREGATE 40 : 60						
1	6.9	1,340	2,020	6.4	1,300	1,940
2	6.4	1,440	1,940	6.5	1,380	1,860
3	6.8	1,360	2,000	6.2	1,300	1,920
4	6.6	1,380	1,980	6.0	1,290	1,930
5	7.0	1,440	1,880	5.9	1,380	1,860
6	6.8	1,350	1,920	6.2	1,280	1,880
7	6.8	1,330	1,910	6.2	1,260	1,840
8	6.6	1,430	1,940	6.2	1,350	1,820
9	7.0	1,320	1,920	6.2	1,260	1,870
10	7.4	1,340	1,800	6.5	1,260	1,830
11	6.7	1,400	1,900	6.5	1,280	1,840
12	6.5	1,440	1,890	6.2	1,360	1,840
13	7.0	1,440	1,800	6.4	1,340	1,790
Average	6.8	1,390	1,920	6.3	1,310	1,860

These figures are given solely to illustrate how fluctuations in material prices affect relative costs and not with any idea that they may be applied to any specific conditions. It should also be noted that, theoretically, there will be a somewhat higher labor cost in placing the gravel due to its extra thickness, although this item might possibly be comewhat neutralized by the greater workability of the gravel concrete as compared with the crushed-stone concrete.

TABLE 16.—*Solid volumes of material for 1 cubic yard of concrete for each mix of series B and total solids or density of concrete expressed as a percentage of maximum possible density*

Coarse aggregate grading No.	Stone				Gravel			
	Solid volumes			Total solids	Solid volumes			Total solids
	Cement	Sand	Stone		Cement	Sand	Gravel	
RATIO OF FINE TO COARSE AGGREGATE 33 : 67								
	Cu. ft.	*Cu. ft.*	*Cu. ft.*	*Per ct.*	*Cu. ft.*	*Cu. ft.*	*Cu. ft.*	*Per ct.*
1	3.11	6.79	12.54	83	2.86	6.54	13.21	84
2	2.97	7.64	12.42	85	2.77	7.34	13.34	87
3	3.26	6.97	12.42	84	2.91	6.54	13.15	84
4	3.08	7.22	12.42	84	3.01	6.54	13.34	85
5	3.06	7.64	12.05	84	2.81	7.10	12.85	84
6	3.40	6.85	11.74	82	3.11	6.36	12.71	83
7	3.30	6.85	11.84	81	2.91	6.54	12.91	84
8	3.01	7.33	11.95	83	2.81	7.03	12.85	84
9	3.11	6.97	12.16	82	2.86	6.54	13.20	84
10	3.54	6.91	11.25	80	3.25	6.36	12.60	82
11	3.35	7.09	11.62	82	3.01	6.54	12.71	82
12	3.25	7.34	11.56	82	2.96	7.15	13.16	86
13	3.40	7.40	11.13	81	3.05	6.84	12.36	82
RATIO OF FINE TO COARSE AGGREGATE 36 : 64								
1	3.21	7.52	12.06	84	2.91	7.22	12.73	85
2	3.06	8.12	11.57	84	2.82	7.76	12.30	85
3	3.30	7.52	11.67	83	2.91	7.22	12.73	85
4	3.11	7.76	11.79	84	2.91	7.16	12.73	85
5	3.01	8.12	11.24	83	2.86	7.70	12.24	84
6	3.40	7.40	11.14	81	3.06	6.91	12.12	82
7	3.11	7.64	11.51	82	2.96	7.03	12.18	82
8	3.01	7.94	11.36	83	2.91	7.58	12.12	84
9	2.96	7.58	11.68	82	2.91	6.91	12.48	83
10	3.60	7.40	10.60	80	3.30	6.79	11.70	81
11	3.30	7.70	11.03	82	3.01	7.15	12.12	83
12	3.11	8.00	11.03	82	3.11	7.52	12.00	84
13	3.30	8.00	10.54	81	3.21	7.39	11.75	83
RATIO OF FINE TO COARSE AGGREGATE 40 : 60								
1	3.35	8.12	10.91	83	3.11	7.88	11.75	84
2	3.11	8.73	10.49	83	3.16	8.36	11.27	84
3	3.30	8.24	10.81	83	3.01	7.88	11.64	83
4	3.20	8.36	10.70	82	2.91	7.82	11.69	83
5	3.40	8.73	10.16	83	2.86	8.36	11.27	83
6	3.30	8.18	10.38	81	3.01	7.76	11.39	82
7	3.30	8.06	10.32	80	3.01	7.64	11.15	81
8	3.20	8.67	10.49	83	3.01	8.18	11.03	82
9	3.40	8.00	10.38	81	3.01	7.64	11.33	81
10	3.59	8.12	9.73	79	3.16	7.64	11.09	81
11	3.26	8.49	10.27	82	3.16	7.76	11.15	82
12	3.16	8.73	10.21	82	3.01	8.24	11.15	83
13	3.40	8.73	9.73	81	3.11	8.12	10.85	32

TABLE 17.—*Average costs per cubic yard of concrete, series A and B*

Series	Coarse aggregate	Ratio of fine to coarse aggregate	Cost of concrete per cubic yard	Average modulus of rupture 28 days
A	Stone	33:67	$5.70	570
	Gravel	33:67	5.38	505
B	Stone	33:67	5.80	586
	Gravel	33:67	5.45	525
	Stone	36:64	5.75	590
	Gravel	36:64	5.40	525
	Stone	40:60	5.75	580
	Gravel	40:60	5.40	515

Costs based on the following assumed unit prices: Cement, $0.60 per bag; sand, $0.50 per ton; coarse aggregate, $1.40 per ton.

CONCLUSIONS PRESENTED

It is not intended that the conclusions given below and which are based on the results of these tests shall be considered as applicable to crushed trap rock and gravel of a different type and quality than those employed in this investigation, or to kindred aggregates produced and marketed under conditions differing from those used, and should not be interpreted as applying to crushed-stone or gravel aggregates in general. These conclusions are as follows:

1. That when coarse aggregates comparable in quality to those used in these tests are employed in the construction of concrete pavements in New Jersey under existing specifications:

(*a*) Concrete in which crushed trap rock is used as coarse aggregate will average about 12 per cent higher in flexural strength than concrete in which gravel is used as coarse aggregate.

(*b*) There will be practically no difference in the crushing strength of crushed trap-rock concrete and gravel concrete.

(*c*) There will be practically no difference in the absorption of crushed trap-rock concrete and gravel concrete.

(*d*) For equivalent flexural slab strengths, a pavement constructed of gravel concrete should have a depth approximately one-half inch greater than a pavement constructed of crushed trap-rock concrete.

(*e*) The cost of the materials required for a unit volume of crushed trap-rock concrete will as a rule be greater than the cost of materials required for an equivalent volume of gravel concrete.

2. That when coarse aggregates comparable to those used in these tests are used in concrete mixtures designed for a given strength by the so-called water-cement ratio trial method:

(*a*) The flexural strength of the crushed trap-rock concrete will average about 11 per cent higher than the gravel concrete.

(*b*) There will be practically no difference in the crushing strength of the crushed trap-rock concrete and the gravel concrete.

In addition to the above, the following indications as to effect of gradation on strength and yield when the concrete is proportioned by fixed volume as well as by the water-cement ratio theory may be stated:

(1) That the gradation of the coarse aggregate has very little direct effect upon the strength of the concrete.

(2) That when proportioned by the water-cement ratio trial method, variations in the fine-coarse aggregate ratio of from 1:2 to 2:3 do not affect the strength of the concrete for a given sand and for a given water-cement ratio.

(3) That variation in coarse aggregate grading will greatly affect the yield of concrete and therefore its cost, when the concrete is proportioned either in the usual way or by the water-cement ratio method.

(4) That the use of well-graded coarse aggregate will increase the yield when proportioned by the usual method, but exactly the reverse is the case when the concrete is proportioned by the water-cement ratio method.

(Continued from page 262)

but it is one which is rather hard on the profits which might otherwise be had from the job.

Table 8 shows a number of typical readings of the time required to move both crawler and wheel-traction type shovels under fair to good field conditions. The average time required for moving the wheel-traction type operating on mats was more than five times that required for moving the improved crawler type. In shallow cuts where much moving is required the shovel equipped with wheel traction operating on mats is under a severe handicap. This is also true for some of the older crawler types which normally require an additional man when moving. In general, and under fair field conditions, it should be possible to keep the average time per move for a ¾-yard crawler type shovel of the better type within 15 seconds and within 75 seconds for a similar shovel equipped with wheel traction and operating on mats. If the average time per move approaches 30 seconds under ordinary field conditions for the crawler shovel or 150 seconds for the wheel shovel, we may safely conclude that either the operator is slow or the mechanism needs adjustment or repair. For blocking or leveling the shovel on steep grades at least two wide wedge-shaped blocks reinforced with strap iron and light bolts should be provided. Such blocks can readily be handled by the pitman and will pay for themselves in a few hours where conditions are such that blocking is required.

TABLE 8.—*Shovel movements classified according to time required*

Time required (seconds)	Movements of crawler-traction shovels	Movements of wheel-traction shovels operating on mats	Time required (seconds)	Movements of crawler-traction shovels	Movements of wheel-traction shovels operating on mats
	Number	*Number*		*Number*	*Number*
8 to 10	6		50 to 60	2	5
10 to 12	29		60 to 70	1	12
12 to 14	32		70 to 80		28
14 to 16	20		80 to 90	2	7
16 to 18	14		90 to 100		10
18 to 20	8		100 to 125		16
20 to 25	23		125 to 150		7
25 to 30	10		150 to 175		4
30 to 35	7		175 to 200		1
35 to 40	8		Above 200		6
40 to 50	6	3			

SHOVEL OPERATOR A MOST IMPORTANT FACTOR

A high degree of efficiency in power-shovel operation can only be secured through the proper coordination of several factors. The first and most apparent is the operator. The ideal operator is a man gifted with quick reaction, a true eye, good judgment, great endurance, and a high degree of skill and experience. He should know the possibilities as well as the limitations of the shovel and be able to maintain it in first-class condition.

But it is not enough simply to secure a good operator. Except where casting is involved, the operator can dig no more material than the available equipment can haul, and he can only dig when hauling units are actually in place for loading. If the supply of wagons or trucks is inadequate to handle full shovel production, or if their operation is such as to interfere with the steady, methodical operation of the shovel, the fault lies with the management.

○

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No. *1132D. The Results of Physical Tests of Road-Building Rock from 1916 to 1921, Inclusive. 10c.
1259D. Standard Specifications for Steel Highway Bridges, adopted by the American Association of State Highway Officials and approved by the Secretary of Agriculture for use in connection with Federal-aid road work.
1279D. Rural Highway Mileage, Income, and Expenditures, 1921 and 1922.
1486D. Highway Bridge Location.

DEPARTMENT CIRCULARS

No. 94C. T. N. T. as a Blasting Explosive.
331C. Standard Specifications for Corrugated Metal Pipe Culverts.

MISCELLANEOUS CIRCULARS

No. 62M. Standards Governing Plans, Specifications, Contract Forms, and Estimates for Federal Aid Highway Projects.
93M. Direct Production Costs of Broken Stone.
*105M. Federal Legislation Providing for Federal Aid in Highway Construction and the Construction of National Forest Roads and Trails. 5c.

FARMERS' BULLETINS

No. *338F. Macadam Roads. 5c.
*505F. Benefits of Improved Roads. 5c.

SEPARATE REPRINTS FROM THE YEARBOOK

No. *739Y. Federal Aid to Highways, 1917. 5c.
*849Y. Roads. 5c.
914Y. Highways and Highway Transportation.

REPRINTS FROM THE JOURNAL OF AGRICULTURAL RESEARCH

Vol. 5, No. 17, D- 2. Effect of Controllable Variables upon the Penetration Test for Asphalts and Asphalt Cements.
Vol. 5, No. 19, D- 3. Relation Between Properties of Hardness and Toughness of Road-Building Rock.
Vol. 5, No. 24, D- 6. A New Penetration Needle for Use in Testing Bituminous Materials.
Vol. 6, No. 6, D- 8. Tests of Three Large-Sized Reinforced-Concrete Slabs Under Concentrated Loading.
Vol. 11, No. 10, D-15. Tests of a Large-Sized Reinforced-Concrete Slab Subjected to Eccentric Concentrated Loads.

* Department supply exhausted.

UNITED STATES DEPARTMENT OF AGRICULTURE

BUREAU OF PUBLIC ROADS

STATUS OF FEDERAL AID HIGHWAY CONSTRUCTION

AS OF

JANUARY 31, 1928

STATES	FISCAL YEARS 1917-1927			FISCAL YEAR 1928									BALANCE OF FEDERAL AID FUND AVAILABLE FOR NEW PROJECTS	STATES
	PROJECTS COMPLETED PRIOR TO JULY 1, 1927			PROJECTS COMPLETED SINCE JUNE 30, 1927			*PROJECTS UNDER CONSTRUCTION			PROJECTS APPROVED FOR CONSTRUCTION				
	TOTAL COST	FEDERAL AID	MILES	TOTAL COST	FEDERAL AID	MILES	ESTIMATED COST	FEDERAL AID ALLOTTED	MILES	ESTIMATED COST	FEDERAL AID ALLOTTED	MILES		
Alabama	$ 20,061,371.68	$ 9,615,099.94	1,400.2	$ 725,370.17	$ 354,700.69	42.1	$ 8,754,097.56	$ 4,254,934.60	510.2	$ 630,145.64	$ 315,072.81	19.9	2,904,349.96	Alabama
Arizona	11,809,950.70	6,447,169.27	800.8	624,598.32	451,055.92	15.7	1,087,792.63	827,674.26	66.1	34,528.88	17,264.44	0.2	3,990,160.11	Arizona
Arkansas	22,337,014.63	9,525,192.75	1,560.6	52,245.29	26,122.64	0.1	4,740,352.25	2,115,027.41	241.0				2,499,142.20	Arkansas
California	35,128,269.04	16,967,026.82	1,306.3	3,685,309.77	1,699,840.46	84.7	7,617,462.96	3,428,674.54	154.2	230,101.00	134,662.03	9.4	4,812,463.15	California
Colorado	15,497,121.91	7,934,298.91	829.0	91,935.74	48,486.64	0.9	7,076,482.68	3,468,895.51	285.1	35,740.10	20,057.34	2.9	3,613,994.60	Colorado
Connecticut	6,397,392.29	2,444,000.54	137.3	1,352,857.40	367,626.33	17.7	5,712,748.89	1,597,373.38	69.6	1,139,177.58	191,246.72	12.0	680,332.03	Connecticut
Delaware	6,237,026.55	2,345,572.42	159.5	486,740.02	232,041.85	29.4	934,367.77	262,068.47	16.3				365,625.26	Delaware
Florida	7,476,856.31	3,627,912.60	245.1	4,068,583.22	1,947,518.78	76.4	5,750,741.38	2,386,757.80	133.0	1,363,436.03	562,525.30	37.8	1,361,001.52	Florida
Georgia	31,951,436.50	15,101,232.40	2,173.6	6,271,289.20	2,984,490.77	225.5	4,512,644.56	2,241,128.26	167.4	454,728.07	227,364.02	34.8	1,836,961.55	Georgia
Idaho	13,225,515.45	7,075,527.16	835.5	1,514,248.94	949,584.29	111.0	2,158,991.84	1,306,363.28	142.3	116,000.00	65,500.00	10.8	1,030,807.27	Idaho
Illinois	48,538,982.16	22,781,516.60	1,530.8	408,484.92	191,977.92	15.0	16,264,820.84	7,681,175.60	538.6	2,138,204.62	1,069,102.31	76.3	4,398,079.57	Illinois
Indiana	23,372,717.74	11,238,568.20	732.5	997,394.00	482,777.27	34.5	16,934,990.86	8,108,138.77	513.2	2,249,564.67	1,017,689.96	80.1	1,205,415.80	Indiana
Iowa	34,306,138.86	14,395,603.75	2,484.4	5,461,954.45	2,558,101.78	334.0	10,537,012.24	4,643,249.80	283.1	2,882,871.37	1,033,579.66	17.4	935,318.01	Iowa
Kansas	37,442,061.61	14,730,829.48	1,495.2	4,065,705.11	1,797,079.21	251.8	12,302,702.10	4,824,488.01	639.4	160,479.77	62,000.00	6.6	2,180,742.30	Kansas
Kentucky	23,216,600.53	9,510,694.75	874.9	1,126,260.03	513,569.73	53.5	9,729,207.57	4,602,263.41	418.9	50,000.00	25,000.00	5.4	1,400,257.11	Kentucky
Louisiana	15,877,552.20	7,093,892.21	1,178.7	1,332,121.58	597,801.48	48.7	3,950,318.64	1,822,681.80	138.4	2,258,092.75	1,111,116.29	83.3	679,506.22	Louisiana
Maine	10,564,800.06	4,858,452.67	357.6	1,606,901.19	594,660.89	51.9	1,632,359.16	594,670.62	43.9	87,912.01	43,956.00	5.6	1,735,312.82	Maine
Maryland	11,790,203.93	5,524,938.27	477.8	774,726.27	354,681.06	42.3	1,441,898.31	696,347.17	62.2				619,115.50	Maryland
Massachusetts	20,670,246.02	7,425,928.15	410.4	773,728.83	158,264.74	9.6	6,742,463.44	1,865,290.01	115.4	529,071.01	201,480.00	13.4	2,635,671.10	Massachusetts
Michigan	31,977,248.37	14,328,484.99	1,084.2	3,276,113.43	1,507,222.57	118.5	13,204,608.57	5,865,815.50	347.6	1,282,964.10	485,027.00	32.3	2,580,101.94	Michigan
Minnesota	45,099,648.47	19,046,145.67	3,643.5	5,852,424.86	2,001,398.90	248.7	3,948,261.25	1,133,100.00	216.6	1,769,628.38	408,000.00	90.8	1,236,471.43	Minnesota
Mississippi	18,331,230.75	9,004,294.62	1,314.1	1,962,875.53	969,021.17	110.6	5,932,705.57	2,865,018.70	303.7	287,398.14	143,699.06	29.9	1,763,592.45	Mississippi
Missouri	42,389,290.41	19,681,026.48	1,944.8	3,675,283.66	1,605,064.63	124.1	7,287,062.27	3,154,252.43	236.0	365,687.27	182,843.62	24.0	2,972,770.84	Missouri
Montana	12,854,995.72	7,287,288.69	1,151.6	421,710.47	310,860.44	51.2	4,127,060.59	2,803,031.44	334.0	1,017,860.68	563,621.41	114.3	5,564,158.02	Montana
Nebraska	16,157,040.25	7,739,386.39	2,246.6	4,294,321.03	2,068,912.12	412.9	11,766,933.85	5,804,015.44	1167.1	490,467.82	242,845.23	48.5	1,950,194.82	Nebraska
Nevada	10,421,349.31	7,589,168.68	853.6	576,886.41	495,568.11	67.8	1,723,110.43	1,504,094.33	186.1	56,261.39	49,352.46	8.7	1,063,536.42	Nevada
New Hampshire	5,868,897.76	2,778,928.05	264.8	694,906.65	315,165.24	23.7	930,323.53	410,717.07	26.1	60,872.73	23,295.[illegible]	1.6	372,636.64	New Hampshire
New Jersey	22,229,240.08	7,495,364.48	316.3	3,[illegible],328.30	1,012,036.00	67.5	3,910,282.53	817,294.17	53.3	236,240.80	77,337.[illegible]	5.5	935,122.00	New Jersey
New Mexico	13,336,250.54	7,937,598.06	1,505.2	810,649.68	535,454.33	67.7	3,182,754.13	2,448,605.46	207.5				2,426,852.15	New Mexico
New York	54,183,085.44	21,693,955.65	1,439.3	4,308,108.63	1,422,554.62	95.7	43,416,936.00	10,565,541.45	656.7	4,636,600.00	909,952.50	58.2	6,718,286.78	New York
North Carolina	35,295,849.21	14,518,903.16	1,460.1	1,568,316.60	729,783.35	63.3	3,296,998.16	1,577,515.52	92.9	151,250.00	74,000.00	6.4	2,246,269.97	North Carolina
North Dakota	15,881,558.55	7,746,293.68	2,715.6	2,949,130.42	1,674,127.76	369.1	4,342,269.12	2,141,697.39	671.4	525,413.30	238,017.11	101.2	1,336,914.06	North Dakota
Ohio	52,621,391.49	19,331,376.76	1,515.0	4,511,431.24	1,978,592.59	156.0	10,220,064.49	3,886,995.03	258.2	2,560,392.00	1,053,795.00	61.2	5,001,209.62	Ohio
Oklahoma	30,381,957.08	14,117,589.21	1,268.1	789,742.25	379,754.99	9.6	6,480,678.84	2,924,596.40	396.5	1,044,745.17	501,281.34	67.5	1,637,522.06	Oklahoma
Oregon	19,583,584.76	10,041,452.94	1,055.0	251,199.81	137,760.88	11.3	2,711,328.63	1,426,367.68	75.5	121,356.96	58,963.27	0.9	1,586,711.23	Oregon
Pennsylvania	77,726,174.22	26,317,620.32	1,534.3	4,413,200.23	1,393,613.17	97.8	17,982,594.54	5,391,479.08	337.3	1,865,518.07	545,839.47	36.0	4,359,749.96	Pennsylvania
Rhode Island	5,233,413.38	1,998,479.06	116.0	700,482.52	227,205.00	15.1	1,448,380.20	389,422.41	23.4	357,495.46	99,990.00	6.6	683,722.53	Rhode Island
South Carolina	17,002,039.93	7,526,988.80	1,568.4	2,124,613.95	1,013,264.39	69.0	8,297,688.91	2,319,625.72	227.7	1,238,736.87	137,000.00	18.0	919,166.09	South Carolina
South Dakota	19,262,063.24	9,507,525.54	2,502.9	497,551.21	264,836.59	98.5	4,872,560.96	2,578,121.58	730.4	512,398.46	219,281.90	92.7	1,041,069.39	South Dakota
Tennessee	24,283,035.03	11,551,457.55	868.7	2,614,430.80	1,167,735.89	65.4	8,018,992.39	3,363,211.14	215.6	1,404,201.48	691,951.06	62.3	1,733,013.36	Tennessee
Texas	78,190,246.37	31,566,960.45	5,466.4	7,981,555.08	3,651,418.03	274.5	13,971,441.56	6,036,209.24	467.5	4,031,493.80	1,532,371.58	120.4	6,819,319.70	Texas
Utah	9,154,377.33	5,767,079.95	628.9	854,916.56	628,347.38	80.5	2,735,358.04	2,035,223.37	169.9	224,936.28	34,628.72	4.0	1,048,498.58	Utah
Vermont	5,037,118.23	2,348,856.01	152.7	1,442,701.40	571,822.67	27.9	1,939,714.80	683,331.78	43.7				395,746.54	Vermont
Virginia	26,844,025.24	12,537,143.25	1,168.9	1,026,780.54	447,174.68	27.3	4,796,157.16	1,930,082.88	103.0	506,966.19	192,019.27	6.6	1,275,355.92	Virginia
Washington	18,184,505.97	8,246,551.95	711.1	1,052,488.88	475,736.32	22.3	4,559,312.97	1,983,270.53	123.3	50,548.85	11,329.47	0.1	1,702,645.73	Washington
West Virginia	10,424,847.32	4,573,748.01	419.4	1,919,689.39	774,876.18	51.4	6,407,489.46	2,681,827.10	228.9	129,443.32	64,721.66	6.7	844,770.05	West Virginia
Wisconsin	27,891,502.16	11,847,868.30	1,729.5	4,462,335.78	2,158,487.04	206.5	8,060,777.68	3,493,549.85	263.1				3,673,596.21	Wisconsin
Wyoming	12,650,712.15	7,139,267.05	1,315.9	1,503,999.96	962,836.11	83.6	2,169,196.59	1,382,696.58	224.1				955,390.26	Wyoming
Hawaii	343,664.15	97,440.00	6.5	160,636.91	70,440.00	4.7	1,624,080.08	491,922.64	25.0				1,171,600.36	Hawaii
TOTALS	1,154,740,601.48	510,007,691.24	60,957.6	105,962,266.63	47,262,452.60	4,567.0	341,146,578.97	140,815,834.61	12950.4	39,288,931.01	14,638,780.36	1,420.3	104,900,241.19	TOTALS

* Includes projects reported completed (final vouchers not yet paid) totaling: Estimated cost $ 116,807,474.19 Federal aid $ 49,285,345.71 Miles 4,470.0